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ANALYSIS AND DESIGN MODIFICATION OF AN AIRBORNE MIRROR ALIGNMEN--ETC(U)
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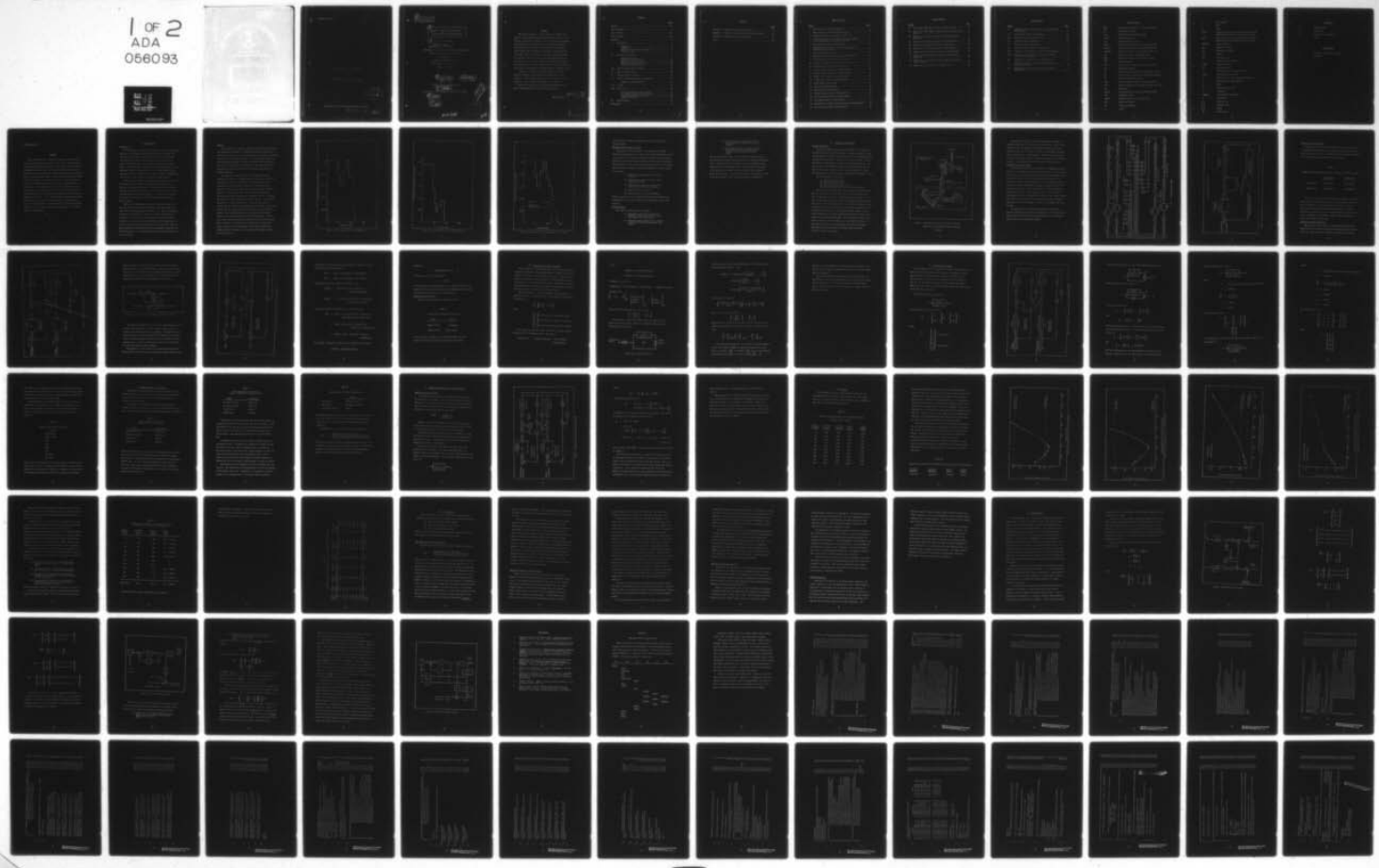

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ANALYSIS AND DESIGN MODIFICATION OF
AN AIRBORNE MIRROR ALIGNMENT SYSTEM

THESIS

AFIT/GAE/AA/78M-12 Patrick D. Nale
2d Lt USAF

Approved for public release; distribution unlimited

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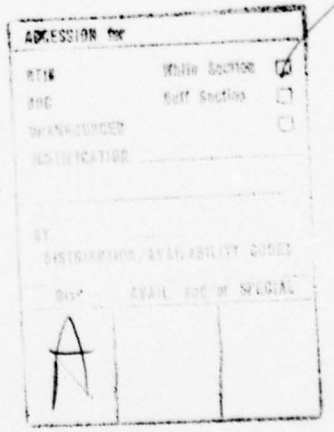
Preface

This thesis attempts to analyze and solve a control system problem of the Airborne Dynamic Alignment System. This system is actually a subsystem of a current Air Force project, the Airborne Laser Laboratory. The Airborne Laser Laboratory is based at Kirtland AFB, NM, and thanks to the people of the LRO branch of the Weapons Lab at Kirtland, I was able to study the problem first hand. They sponsored me in this thesis and also provided the opportunity for a four week stay at Kirtland AFB during the initial phase of this study. Special thanks are due Capt Garth Corey of LRO, who spent many hours walking me through the difficult first steps of understanding the Airborne Dynamic Alignment System.

I also wish to express my sincere appreciation to Capt Gary Reid and Capt Jim Silverthorne who comprised my thesis committee. Without their help and guidance I would never have learned as much as I did while working on this thesis.

Finally, I would like to thank my loving wife, Joyce, who kept me alive during this difficult learning period.

Patrick D. Nutz



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$[A]$	Matrix that is dependent on system components
AAS	Auto Alignment System
ADAS	Airborne Dynamic Alignment System
A(DIS)	Angular disturbance
ALL	Airborne Laser Laboratory
ALPHA	Angular rotation axis of beam steering mirrors
ALPHA(1)	ALPHA axis rotation of beam steering Mirror #1
ALPHA(2)	ALPHA axis rotation of beam steering Mirror #2
APT	Automatic Pointing and Tracking Device
$[B]$	Matrix which represents the external inputs
BAS	Beam Angle Sensor
BETA	Angular rotation axis of beam steering mirrors
BSM	Beam Steering Mirror
C_1	Signal leaving Y-Translation compensation network
C_2	Signal leaving ALPHA-Prealign compensation network
$\hat{d}$	Estimated disturbance vector
E(A)	Error in angular alignment of main laser beam
E(T)	Error in translational alignment of main laser beam
FM	Fold Mirror
FRQRSP	Frequency Response Computer Simulation Program
GDL	Gas Dynamic Laser
GLOWPS	Transfer function for low pass filter
HPG	High Power Grating
Hz	Hertz, cycles/second
in	inches

J	Cost function
j	$\sqrt{-1}$
lb	Pound
KA1AP	Electronic cross-coupling sensitivity between the ALPHA-Prealign and Y-Translation control loops
KA2YT	Electronic cross-coupling sensitivity between the ALPHA-Prealign and Y-Translation control loops
NODE2SIG	Signal at Node #2
PAS	PreAlignment Sensor
PSD	Power Spectral Density
rad	Radians
RMS	Root Mean Square
s	Laplace transform variable
SIGMA	Standard deviation
SOW	Statement Of Work
T	Cutoff frequency of low pass filter
T(DIS)	Translational disturbance
W	White noise, zero mean, Gaussian statistics
w	Frequency, hertz (Hz), rad/sec
X	State
$\hat{\underline{x}}$	Estimated state vector
Y	Y direction
YTERSIG	Y-Translation error signal
Z	Z direction
$\rightarrow$	To or goes to
$\lvert\ \rvert$	Absolute value
[ ]	Matrix
$\angle$	Greater than

Subscripts

A	Angle, angular
d	Disturbance
T	Translation, translational
x	State

Super Scripts

•	Derivative (with respect to time)
^	Estimated

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Abstract

This study deals with an electronic control system modification to solve a torque limitation problem in the Airborne Dynamic Alignment System aboard the Airborne Laser Lab. This control system is reduced in complexity and modeled in the frequency and state space domains. Closed loop system response over a desired frequency range is obtained from the frequency domain model. Stability data is calculated through eigenvalue analysis of the state space model. A low pass filter is introduced to decrease the demand on the torque saturated motor. The main result of this modification is that the filter does not appreciably alter the closed loop response. This is due to the fact that the cutoff frequency of the filter must be extremely high to keep the modified system stable. It is concluded that the complimentary filter does not solve the torque saturation problem. A recommendation is made that further analysis be concentrated in the time domain through modern state space techniques and the design approach to an optimal controller is presented.

I. Introduction

Background

The background of the mirror alignment system lies in the design progression of the Airborne Laser Lab (ALL) based at Kirtland AFB, Albuquerque, New Mexico. The mission of the ALL is to demonstrate the technology involved in firing a laser from an aircraft in an actual flight environment. This project was divided into several phases. The initial phases involved the design and fabrication of the individual components aboard the ALL. In the final phases all the components will be installed in the aircraft and tested. Immediately, the need for certain subsystems to the ALL was acknowledged.

These included the actual beam generation mechanism: specifically the Gas Dynamic Laser (GDL), and a highly specified Automatic Beam Pointing and Tracking (APT) device. Upon further analysis, however, the need for an active beam alignment system between the laser and the pointing/tracking device became apparent. The main catalyst behind this need was the unique vibrational environment encountered in a flying aircraft.

The ALL is a highly modified KC-135 (Boeing 707) aircraft. An aircraft of this size would have significant structural vibrations that would cause misalignments in the laser beam. This is especially critical due to the fact that the ALL is carrying the GDL which is primarily a turbojet engine. Therefore the vibration of the GDL coupled with the normal twisting and bending of the aircraft present quite an adverse vibrational environment to the laser beam. Thus, the Airborne Dynamic Alignment System (ADAS) was designed to eliminate any beam misalignment due to structural flexures of the ALL and the vibration of the GDL.

Problem

The main problem in designing the ADAS was quantitatively defining the vibrational environment. A considerable amount of information on the structural vibration of an ordinary KC-135 is available. Nonetheless the ALL was not an ordinary airplane. For example, major structural modification was necessary to install the GDL and a hole was cut in the roof of the aircraft to mount the APT. Also, there was little information on just how the GDL vibrations would couple with the aircraft vibrations.

With all this in mind, a "first cut" approximation of the vibrations was derived. A complex mathematical model of the ALL was obtained and a "Nastran" based (Ref. 2) structural analysis was performed. The result of this effort was the ADAS Statement Of Work (SOW) Power Spectral Density (PSD). (Ref. 3:2.29 and see Fig.'s 1 and 2). It was with this ADAS SOW disturbance spectrum that Perkin-Elmer designed the actual ADAS hardware. (Ref. 6). The system was delivered to the Air Force to be used in the ALL. It was tested and found to be within specifications. Using a small laser for testing, the ADAS and APT were installed in the aircraft. Flight tests revealed that the actual vibrational environment was worse than predicted. There were significant large magnitude, high frequency vibrations that were not present in the SOW PSD for ADAS. Furthermore, these large magnitude high frequency disturbances were causing ADAS to saturate. Essentially, the system could not respond fast enough to null the beam misalignment. Since this knowledge was a result of CYCLE II testing, the new vibration PSD became the CYCLE III PSD (see Fig. 3).

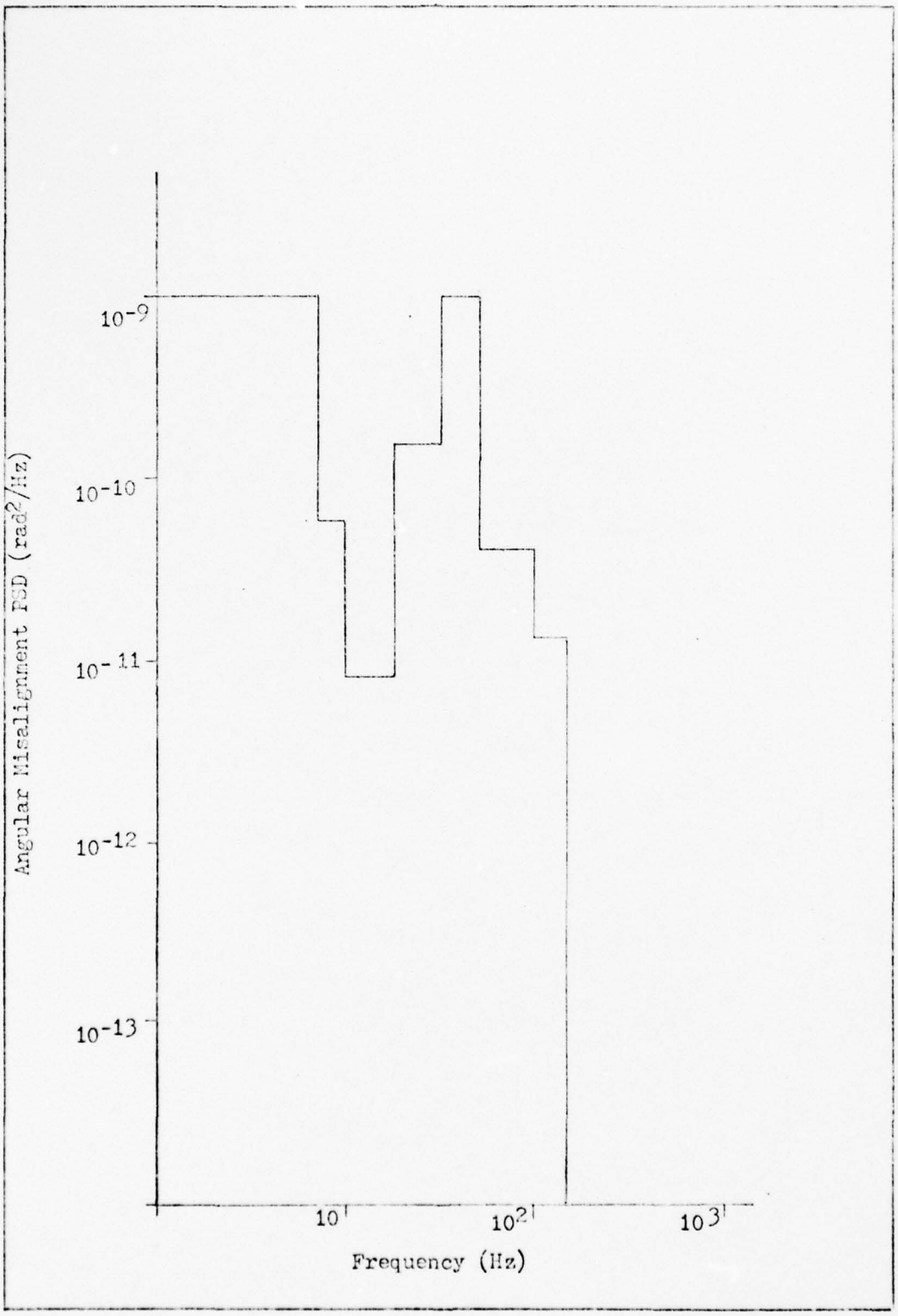


Fig.1 . ADAS Statement of Work PSD (Angular)

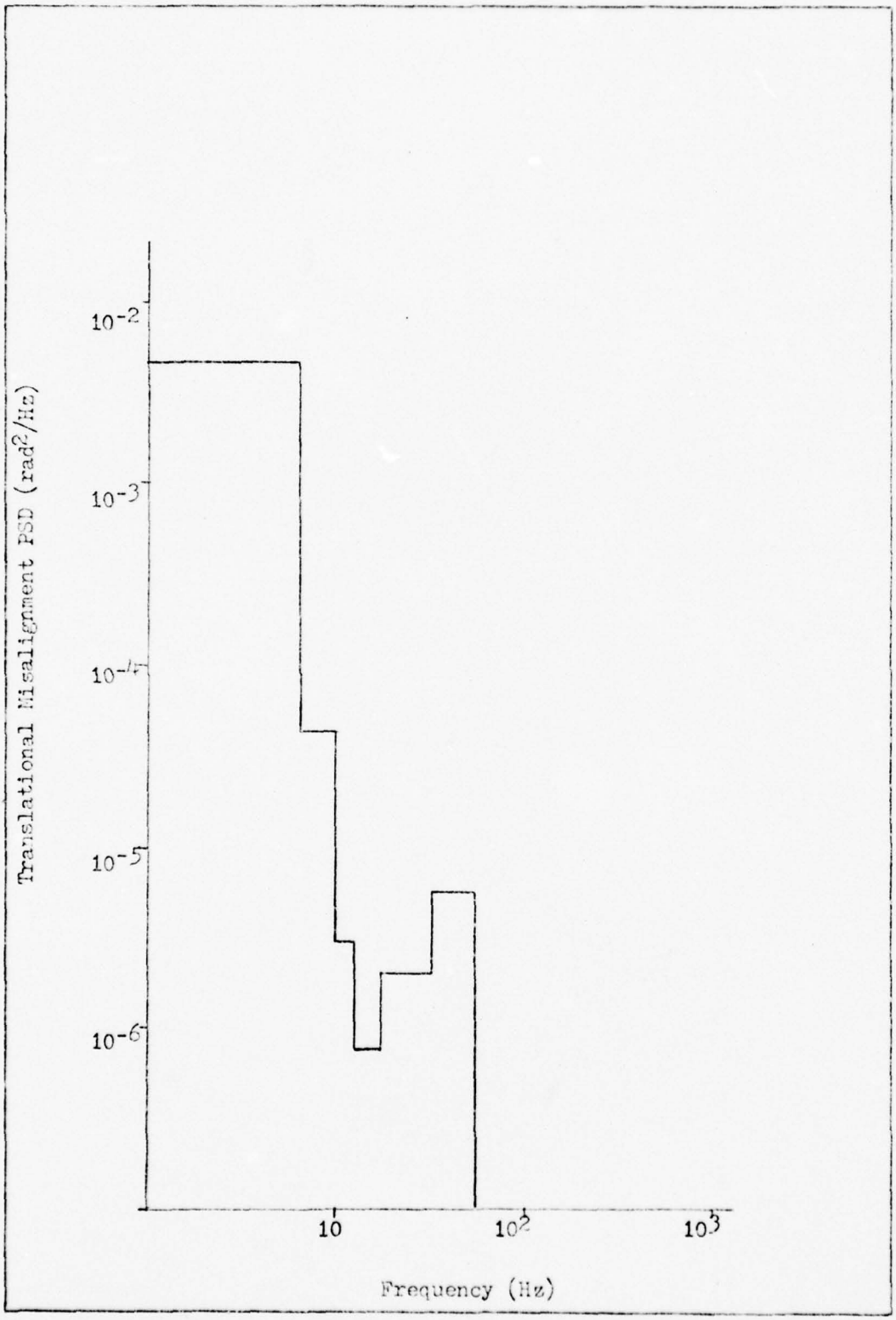


Fig.2 . ADAS Statement of Work PSD (Translational)

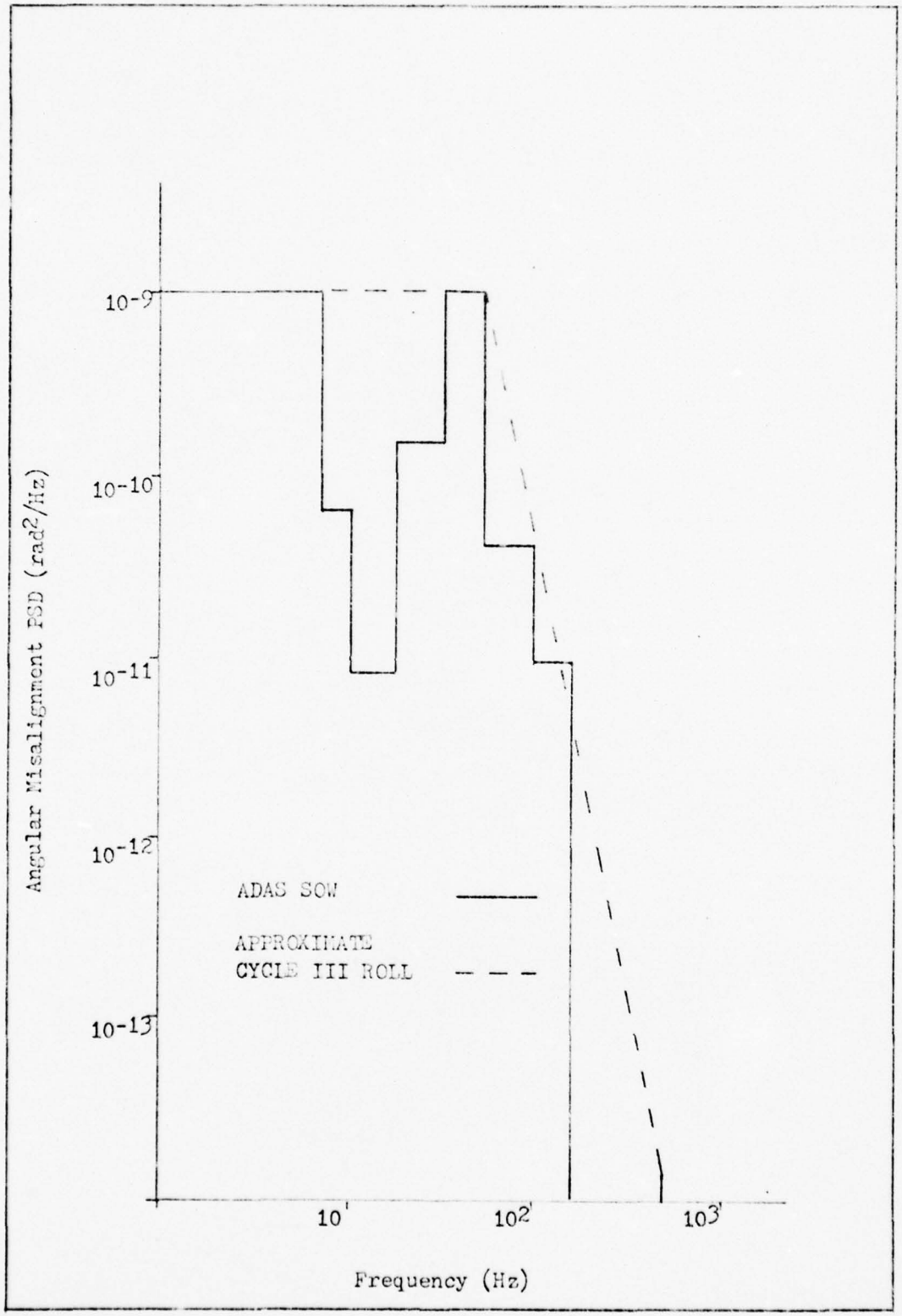


Fig. 3 . Comparison of ADAS SOW and CYCLE III ROLL PSD

and a decision was made to improve ADAS to meet this new input disturbance PSD.

General Problem Solution Approach

The reason the ADAS saturates in the presence of the high frequency disturbances is the torque limit of the mirror actuator motors. In this report it is proposed to accept the torque limit that exists and correct the problem through electronic control system modification. This is possible because the present translation error is very low and more error may be tolerated. The general approach to find a solution is as follows:

1.) Conduct an indepth analysis of the present ADAS.

2.) Quantitatively define the extent of the saturation problem.

3.) Mathematically simplify the present system for ease of analysis and design.

4.) Modify the control system.

5.) Examine results of above modification.

Finally, conclusions will be drawn from the above investigation and recommendations for further action will be made based on those conclusions.

Limits of Study

The limits of this study are as follows:

1.) Modification will deal only with the electronic control system, and no hardware changes were investigated.

2.) Frequency domain analysis will be limited to using the ADAS frequency domain simulation.

3.) All electronic non-linearities in the frequency domain simulation of ADAS are ignored.

4.) No attempt was made to examine the interactive effects of ADAS modification on the APT or the Auto Alignment System (AAS).

The non-linearities in ADAS are in the form of a current limit in the compensation networks and a torque limit to each mirror-acctuator motor. Ignoring the limits will allow use of a completely linear representation of the control system. The RMS value of the signal in the compensation networks and to each motor will be computed during the simulation. In this way, violations of the limits and the resulting saturation of the control system will be identified.

II. Analysis of Present ADAS

General Description

The Airborne Dynamic Alignment System (ADAS) is a subsystem of the Airborne Laser Lab (ALL) and serves to maintain alignment between the Gas Dynamic Laser (GDL) and the entrance of the Automatic Pointing and Tracking device (APT). The ADAS is mounted to the APT. In this way there is no misalignment problems between the APT and ADAS. The two sources of beam vibration or "jitter" come from the GDL and the flexure of the ALL. Since the ADAS is not hard mounted to the GDL, the aircraft flexure is considered the larger beam misalignment source.

The ADAS included the following;

A. translation sensor (TS)
B. prealignment sensor (PAS)
C. beam angle sensor (BAS)
D. two beam steering mirrors (BSM)
E. associated power sources and control electronics

The PAS and TS each have their own active light source. (Ref. 4). This is to allow the use of the PAS and TS before the actual laser beam is generated. The BAS is used only during the operation of the GDL. It maintains a constant "sample" of the precise angular position of the beam. All three sensors, PAS, TS, and BAS are utilized to sense misalignments from a nominal position and feed this information to the electronic control system. The translation sensor measures translational misalignment in the ADAS optical train between the GDL and the translation sensor Fold Mirror (FM). The prealignment sensor measures angular alignment between the GDL and its fold mirror (PAS FM). The beam angle sensor gets its sample of the main beam from the High Power Grating (HPG) and senses the precise angle of the beam between the grating and the GDL.

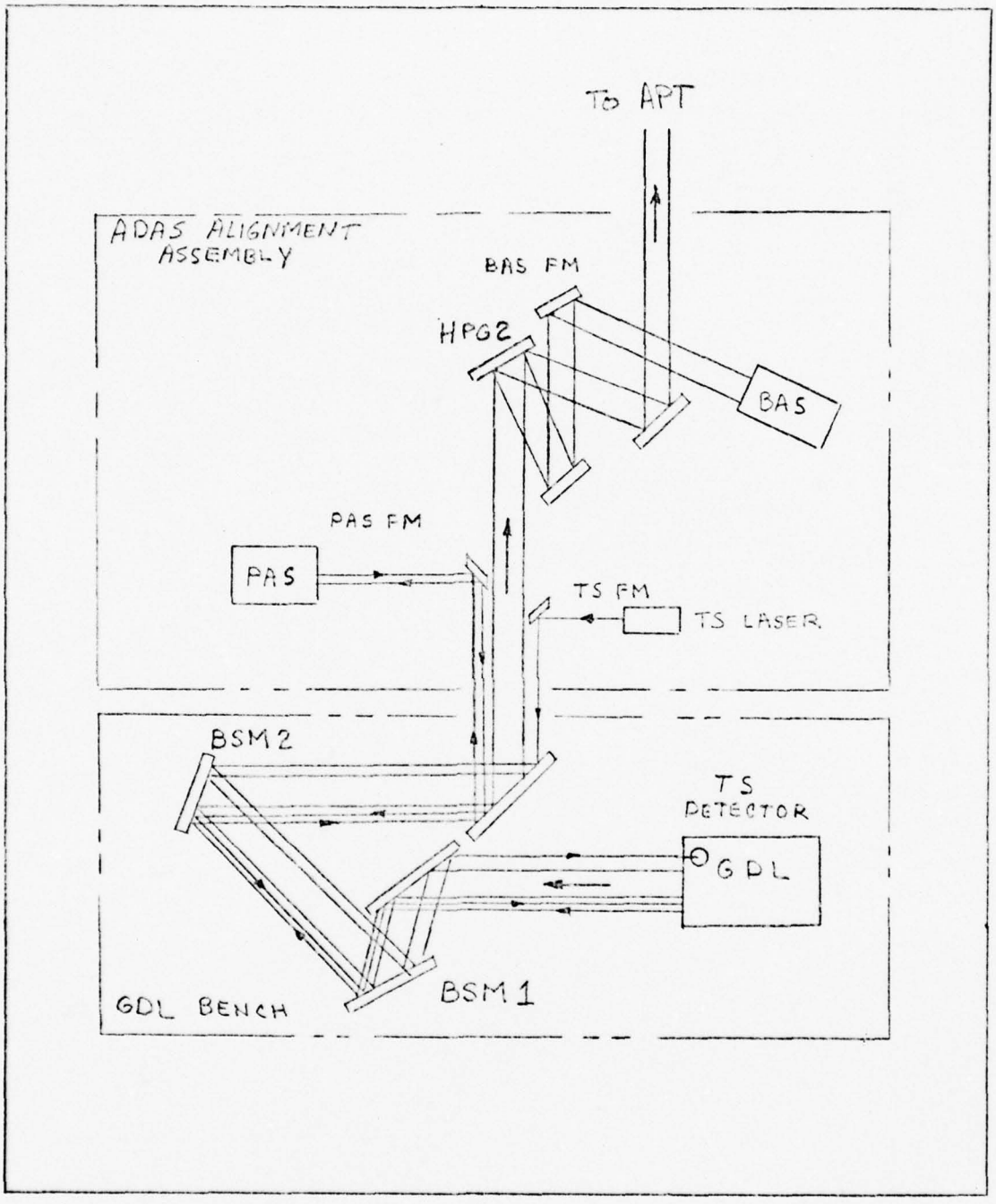


Fig.4. Functional Diagram of the Optical Train and Components of the Airborne Dynamic Alignment Assembly

The electronic control system uses this sensor information to command the movement of the two beam steering mirrors. The two beam steering mirrors are mounted to an optical bench which is in turn mounted to the floor of the ALL. The stop to stop angular displacement of each mirror is 10 microradians. Vibration isolation mounts are used on the bench and GDL to effectively reduce their vibrational coupling. The functional layout of the ADAS is shown in Fig. 4.

The Electronic Control System

The control system works in essentially two independent channels. These are the Y-ALPHA channel and the Z-BETA channel. Y and Z are the two translational errors and ALPHA and BETA are the two angular errors. Each of the two mirrors has two separate axes of rotation. Two separate mirrors are necessary because it is not physically possible to null out angular error without inducing translational error with only one mirror. (Ref. 3:2.4, and Appendix B). The block diagram of the control system is shown in Fig. 5. Each of the four loops is functionally the same. A representative single loop is shown in Fig. 6. Each loop basically consists of a compensation network, electronic decoupling, mirror-motor dynamics, optical cross coupling, and unity feedback.

The electronic cross coupling is necessary to decouple the physical (optical) cross coupling. Essentially, it is with this electronic decoupling networks that translational error is not induced while nulling a pure angular disturbance.

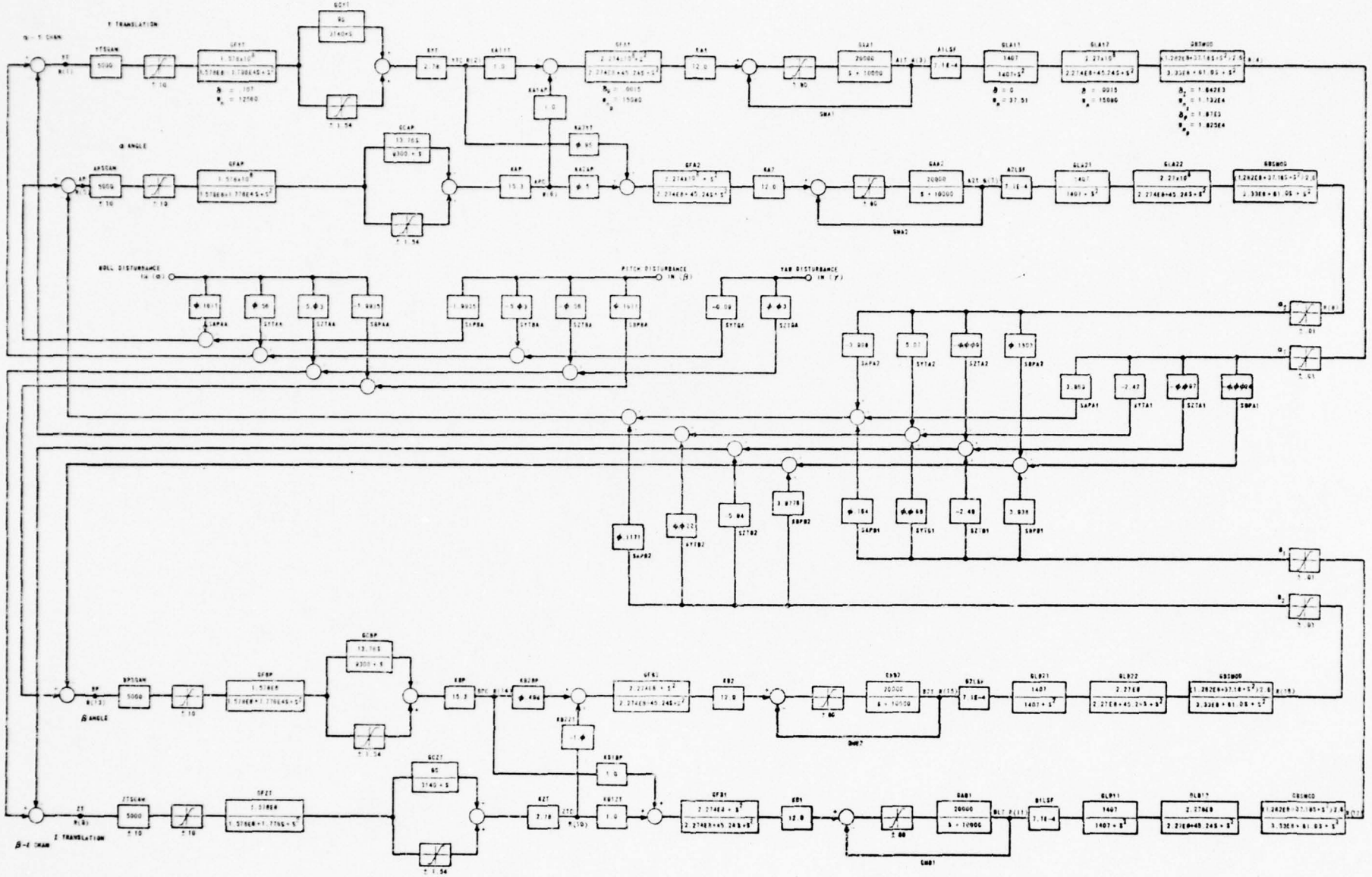


Fig. 5. ADAS FREQUENCY RESPONSE BLOCK DIAGRAM

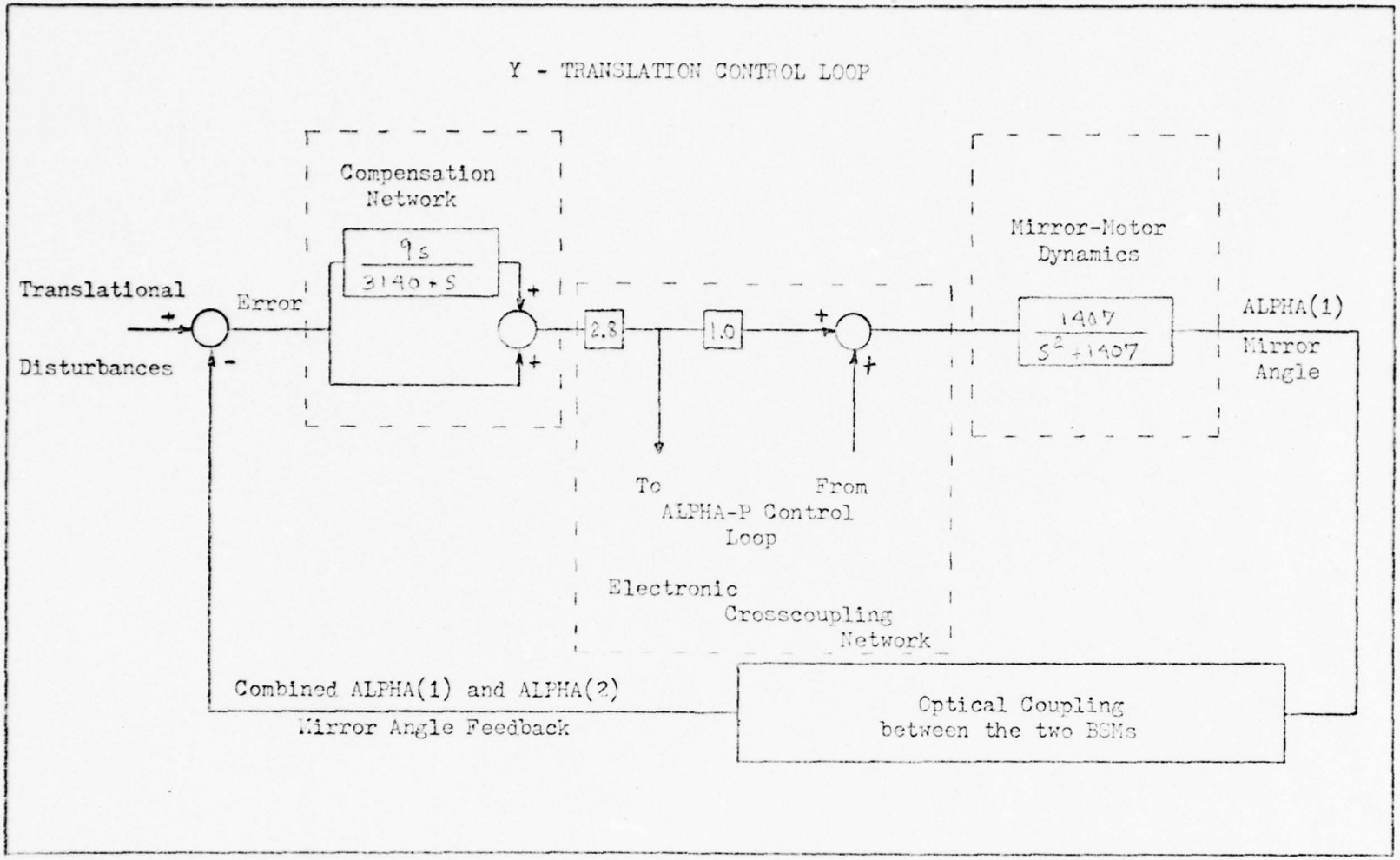


Fig. 6. Representative Single Loop in ADAS Block Diagram of Electronic Control System

Reduction of Control System

Reduction of the four loop control system to a two loop system is straightforward considering the sensitivity coefficients between the control loops (Fig. 5). Furthermore, this will reduce the difficulty in understanding and handling the control system.

Table I

Comparison of Error Output Between 4 Loop and 2 Loop Control System

	4 Loop System	2 Loop System
Y-TRANS Error	4.164 inches	4.165 inches
ALPHA-P Error	1.707 radians	1.705 radians

In Table I, the results of the reduction are shown. This is the error output with the ADAS SOW input at the ALPHA-P disturbance point with no modification to the control system. The two loop system gives almost exactly what the four loop system gives. Therefore, the two loop system (Fig. 7) will be used in place of the four loop system. Essentially, the Y-TRANS — ALPHA-P loops are exactly the same as the Z-TRANS — BETA-P loops.

Need for Electronic Decoupling

The fact that there is optical coupling between the two beam steering mirrors necessitated electronic decoupling between the control loops. Each mirror has an ALPHA and a BETA axis of rotation.

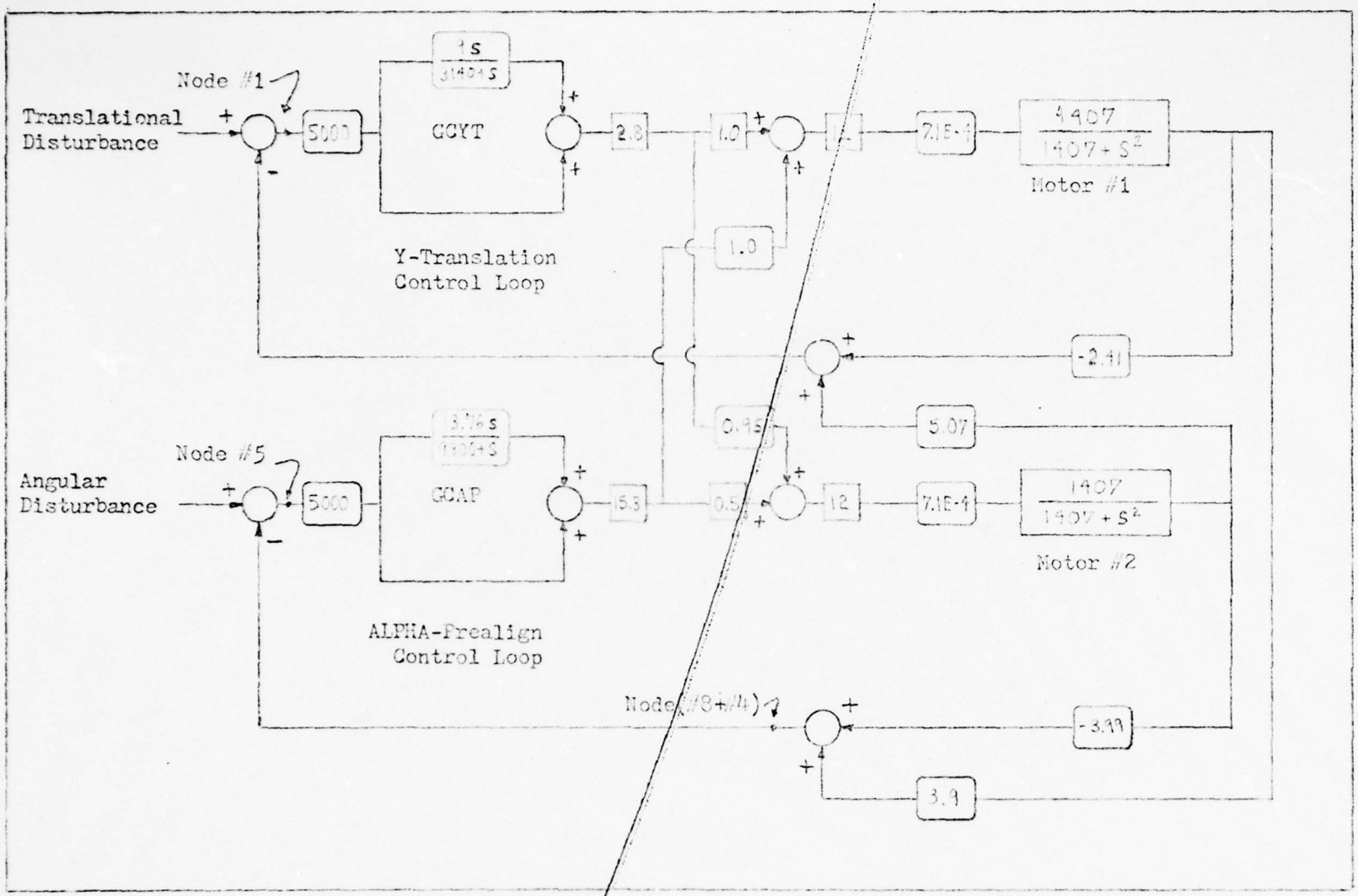


Fig.7 . Two Loop ADAS Control System

They are defined so that ALPHA of mirror #1 couples with ALPHA of mirror #2 and the same for the BETA axis. The electronic decoupling network for the Y-TRANSLATION and the ALPHA-PREALIGN control loops is shown in Fig. 8. This cross-coupling is of the same form as that between the Z-TRANSLATION and BETA-PREALIGN control loops.

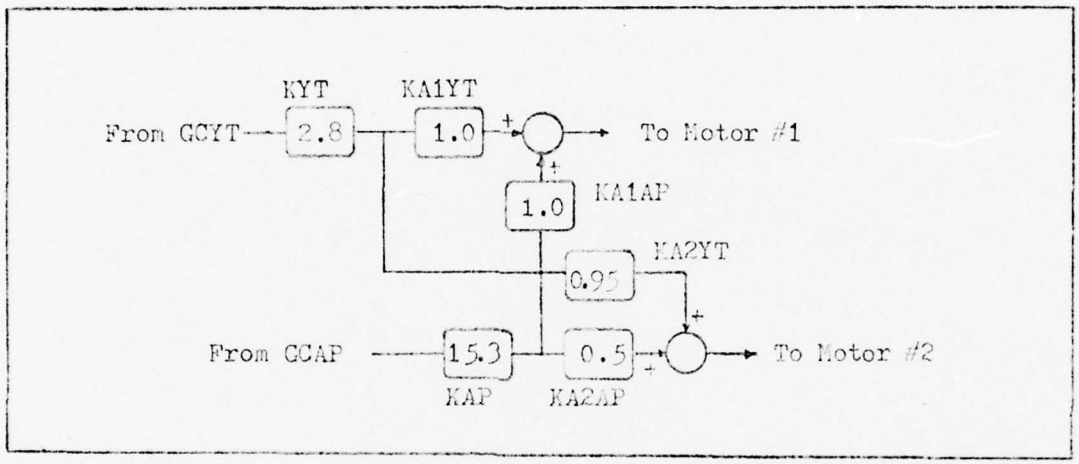


Fig. 8. ALPHA-P, Y- TRANS Electronic Crosscoupling Network

The Y-TRANS and ALPHA-P control loops are shown separated from the main block diagram in Fig. 9. In this figure, however, only the constant gains and sensitivities are included. The electronic cross-coupling sensitivities (KA1AP and KA2YT) are labeled A and B respectively. The high frequency blocks are also not included for further simplification. In this way the control loops are as they would be at a very low frequency ($s \rightarrow 0$) condition.

The equations for each error will be written and the values of A and B will be found such that a pure angular disturbance (A(DIS)) will

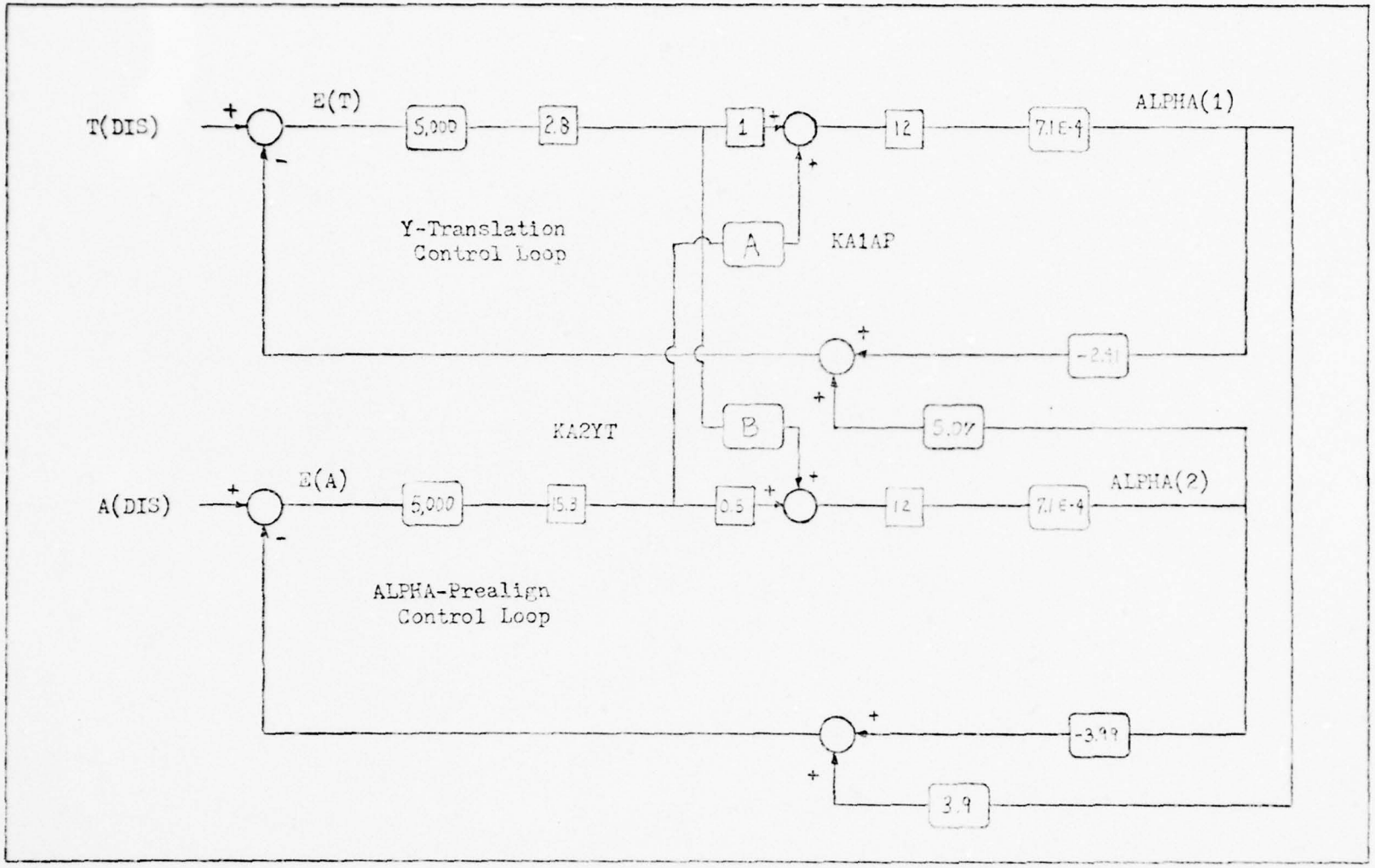


Fig. 9. D.C. Version of ADAS 2 Loop Control System

not induce a translational disturbance (T(DIS)). Equations describing the errors E(T) and E(A) are:

$$E(T) = T(DIS) + 2.41\ ALPHA(1) - 5.05\ ALPHA(2)$$

$$E(A) = A(DIS) + 3.998\ ALPHA(2) - 3.86\ ALPHA(1)$$

The equations describing ALPHA(1) and ALPHA(2) are:

$$ALPHA(1) = (12)\ (7.1E\text{-}4)\ (2.78)\ (5000)\ (E(T)) + (B)\ (2.78)\ (5000)\ E(A)$$

$$ALPHA(2) = (12)\ (7.1E\text{-}4)\ (0.477)\ (15.3)\ (5000)\ (E(A)) + (B)\ (2.78)\ (5000)\ E(T)$$

Substituting ALPHA(1) and ALPHA(2) into the E(T) equation:

$$E(T) = T(DIS) + (2.41)\ (118.4)\ E(T) + A(651.8)\ E(A) - 5.05\ (310.9)\ E(A) + B(118.4)\ E(T)$$

$$= T(DIS) + (285.3)\ E(T) + A(1570.8)\ E(A) - B(598)\ E(T) - (1570.05)\ E(A)$$

$$= T(DIS) + (285.3 - 598B)\ E(T) + (1570.8A - 1570.05)\ E(A)$$

Now in order to make E(T) a function only of T(DIS) and not of E(A):

$$(1570.8A - 1570.05) \text{ MUST EQUAL } 0$$

Therefore:

$$A = (1570.05)/(1570.8) = 1.0$$

By the same process B is found to be:

$$B = 0.965$$

In the original block diagram (Fig. 5), A = 1.0 and B = 0.95, so the electronic cross-coupling (decoupling) does indeed decouple the angle and translation control loops at low frequencies.

Discussion of Error Limits

The error limits specified in the ADAS SOW are:

Table II

Error Limits In Angle And Translation

Signal	Limit
ALPHA-P, BETA-P	3.0 radians
Y-TRANS, Z-TRANS	2,500.0 inches

In the interest of keeping this report unclassified, the exact scale of the limits and closed loop response is not exact.

III. ADAS Frequency Domain Simulation

ADAS is modeled in the frequency domain through a general purpose program called FRQRSP. FRQRSP was developed at Oklahoma State University (Ref. 4) for the Air Force Weapons Laboratory. FRQRSP solves a system of simultaneous linear equations by the Gauss-Jordan elimination method over a specified frequency range. The program is capable of accepting input information in several modes including disturbance spectrum data such as the ADAS SOW and CYCLE III PSD.

ADAS was modeled by a set of 16 equations, each representing a particular node in the control system. The 16 equations are written in the matrix form:

$$\begin{bmatrix} A \end{bmatrix}\begin{bmatrix} R \end{bmatrix} = \begin{bmatrix} B \end{bmatrix}$$

where

$\begin{bmatrix} R \end{bmatrix}$ is the vector of the unknown states

$\begin{bmatrix} B \end{bmatrix}$ is the vector of inputs to the system

$\begin{bmatrix} A \end{bmatrix}$ is the matrix that describes the system

As an example of the way in which the system is modeled, examine the equation for Y-Translation error. From Fig. 7:

$$\text{Y-TRANS Error} = \text{Y-TRANS Disturbance} - (-2.41)\ \text{ALPHA(1)} - (5.07)\ \text{ALPHA(2)}$$

where:

ALPHA(1) is the Angle of Mirror #1

ALPHA(2) is the Angle of Mirror #2

Rearranging the equation:

Y-TRANS Error + (-2.41) ALPHA(1) + (5.07) ALPHA(2) = Y-TRANS Disturbance

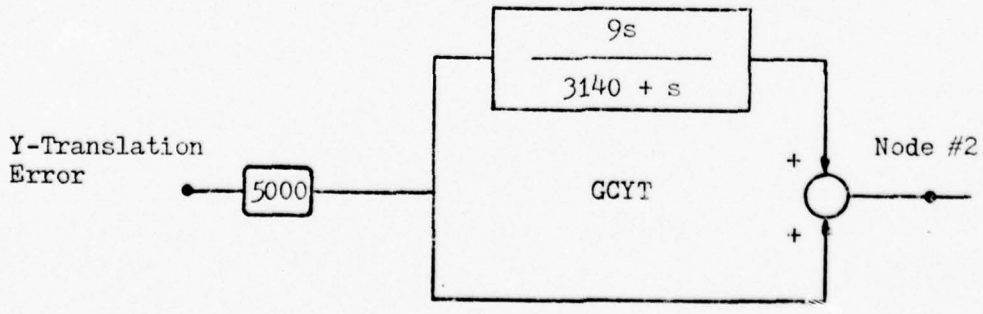
In matrix form:

$$\begin{bmatrix} 1 & -2.41 & 5.07 \end{bmatrix}_{1X3} \quad \begin{bmatrix} \text{Y-TRANS Error} \\ \text{ALPHA(1)} \\ \text{ALPHA(2)} \end{bmatrix}_{3X1} = \begin{bmatrix} \text{Y-TRANS} \\ \text{Disturbance} \end{bmatrix}_{1X1}$$

Thus the Y-TRANS Error equation is in the form:

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} R \end{bmatrix} = \begin{bmatrix} B \end{bmatrix}$$

As an example in which the frequency sensitive portions of the control system are modeled, examine the compensation network in the Y-Translation control loop:



(This segment taken from Fig. 7)

Let the signal at Node #2 equal NODE2SIG and let the Y-Translation error signal equal YTERSIG. Then:

$$\text{NODE2SIG} = (\text{YTERSIG})\,(5000)\left[\frac{9s}{3140 + s} + 1.0\right]$$

$$= \text{YTERSIG}\left[\frac{45{,}000s}{3140 + s} + 5000\right]$$

$$= \text{YTERSIG}\left[\frac{1.57E + 7 + (5.0E + 4)s}{3140 + s}\right]$$

Rearranging this equation:

$$\left[\frac{1.57E + 7 + (5.0E + 4)s}{3140 + s}\right]\left[\text{YTERSIG}\right] = \left[\text{NODE2SIG}\right]$$

which is in the correct form of:

$$\left[\,A\,\right]\left[\,R\,\right] = \left[\,B\,\right]$$

This procedure is followed for the other 14 nodes and then all the equations are combined. The result is a system of equations in the form:

$$\left[\,A\,\right]_{16X16}\left[\,R\,\right]_{16X1} = \left[\,B\,\right]_{16X1}$$

Since the frequency response of the system is desired, replace s by jw. Then evaluate $[A]$ at a particular frequency w and the result is a complex $[A]$. The complex $[A]$ matrix is then inverted and multiplied with $[B]$ to result in a complex $[R]$. The

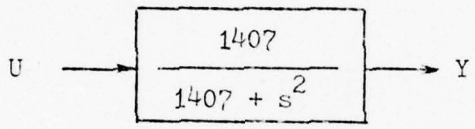
procedure is then repeated for a certain range of frequencies. The overall result is then the complete system response over that certain range of frequencies.

The computer simulation model of ADAS is limited in that it is not possible to model the nonlinearities such as motor torque limits and current limits. It is also not possible to program multiple inputs. However, once the system of equations is solved, output may come from any node.

IV. ADAS State Space Model

ADAS is modeled in state space form to satisfy the need for more precise stability information. This section will develop the state equations, and the shaping filters designed to simulate the input disturbance PSDs. The states of the control system are labeled in Fig. 10. In this particular figure, only the Y-TRANS and ALPHA-P control loops are shown. The figure would be exactly the same for the Z-TRANS BETA-P control loops.

The block diagram for each motor is:



The state equations for each motor is:

$$\dot{\underline{X}} = \begin{bmatrix} 0 & 1 \\ -1407 & 0 \end{bmatrix} \underline{X} + \begin{bmatrix} 0 \\ 1407 \end{bmatrix} U$$

where:

$$\underline{X} = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}, \text{ for motor \#1}$$

$$= \begin{bmatrix} X_3 \\ X_4 \end{bmatrix}, \text{ for motor \#2}$$

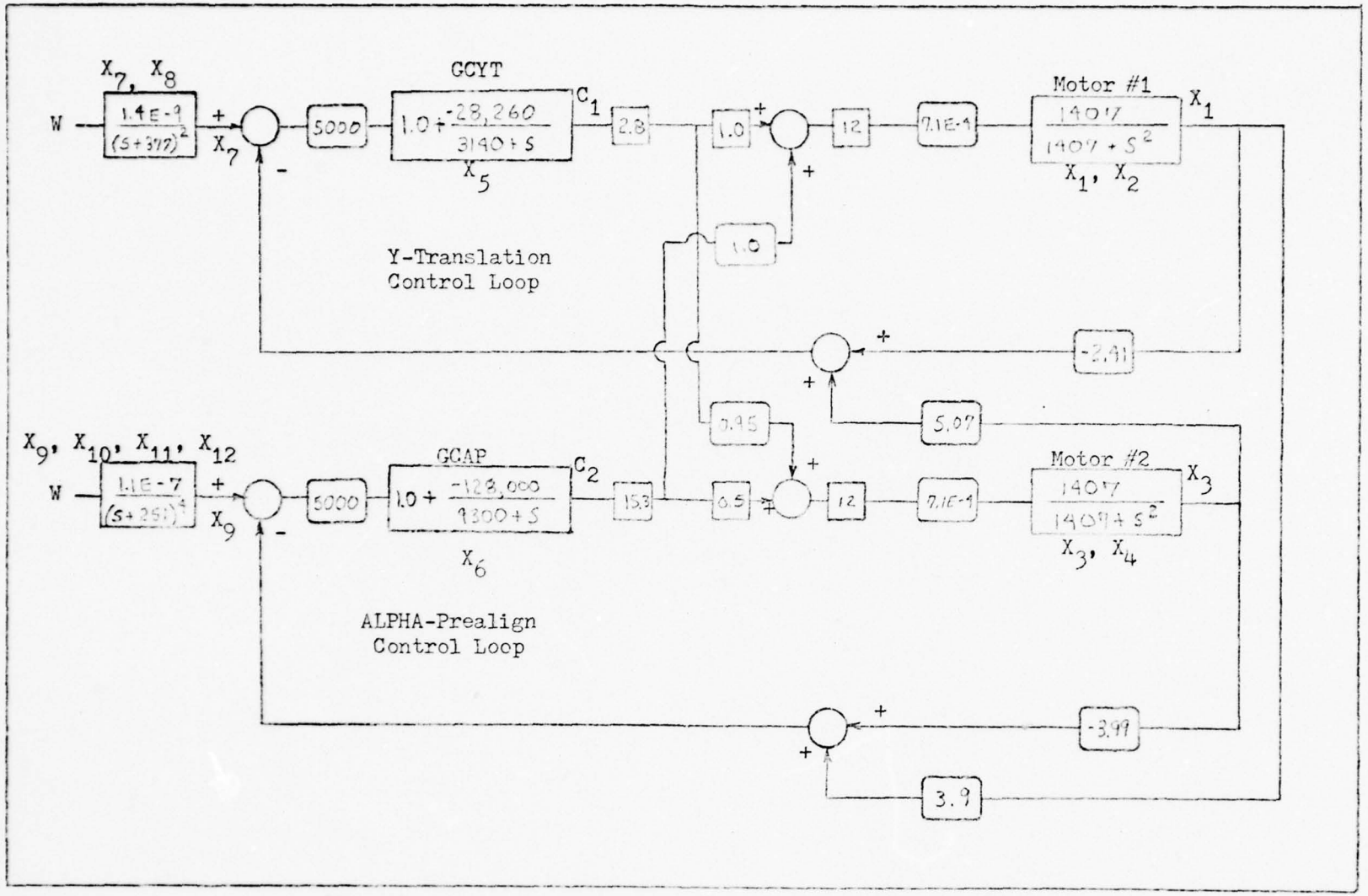
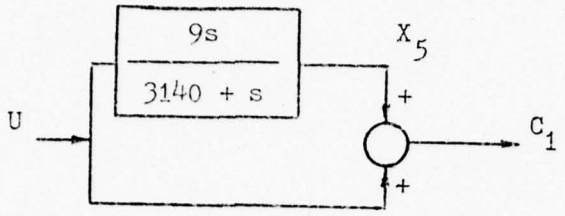
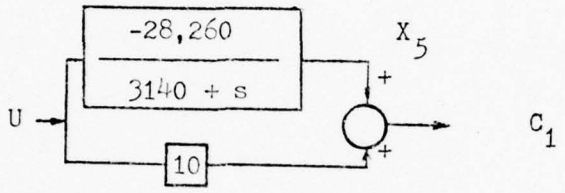


Fig. 10. Location of States in ADAS Two Loop Control System

The actual block diagram for the Y-TRANS (GCYT) compensation is:



This block diagram may be written as:



The X_5 state equation is:

$$X_5 = \left[-3140\right] X_5 + \left[-28,260\right] U$$

and

$$C_1 = \left[1\right] X_5 + \left[10\right] U$$

The state representation of the ALPHA-P compensation is the same form as the Y-TRANS representation. It contains state X_6 and the equation for X_6 is:

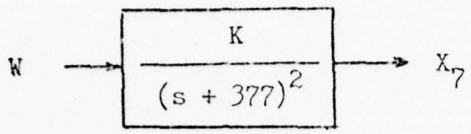
$$X_6 = \left[-9,300\right] X_6 + \left[-127,953\right] U$$

and

$$C_2 = \left[1\right] X_6 + \left[14.76\right] U$$

The input disturbances must be approximated by white noise passed through a shaping filter. The shaping filter for the ADAS SOW PSD

for the Y-TRANS control loop is:



where

W = white noise, zero mean, Gaussian statistics

K = 0.141E-10

$$\frac{X_7}{W} = \frac{K}{s^2 + Bs + C}$$

B = 7.54E+2

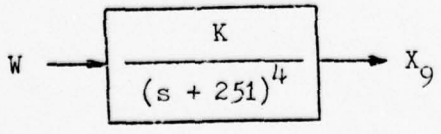
C = 1.42E+2

The state equations are:

$$\dot{X} = \begin{bmatrix} 0 & 1 \\ -C & -B \end{bmatrix} X + \begin{bmatrix} 0 \\ K \end{bmatrix} W$$

$$X = \begin{bmatrix} X_7 \\ X_6 \end{bmatrix}$$

The shaping filter for the ADAS SOW PSD for the ALPHA-P control loop disturbance is:



where

W = white noise, zero mean, Gaussian statistics

K = 0.110E-8

$$\frac{X_9}{W} = \frac{K}{s^4 + Bs^3 + Cs^2 + Ds + E}$$

B = 1.0E+4

C = 3.78E+5

D = 6.34E+7

E = 3.97E+9

The state equations are:

$$\dot{X} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -E & -D & -C & -B \end{bmatrix} X + \begin{bmatrix} 0 \\ 0 \\ 0 \\ K \end{bmatrix} W$$

where

$$X = \begin{bmatrix} X_9 \\ X_{10} \\ X_{11} \\ X_{12} \end{bmatrix}.$$

The origin of these shaping filters is better understood by plotting the magnitude versus frequency curves for the ADAS SOW and approximate disturbances. These plots for the Y-TRANS and ALPHA-P control loops are shown in Fig.'s 27 and 28 respectively.

The combined state space $[A]$ matrix is shown in Fig. 24 in Appendix C. The eigenvalues of this $[A]$ matrix correspond to the roots of the characteristic equation of the closed loop transfer function. The eigenvalues for this control system are shown in Table III.

Table III

Eigenvalues of ADAS Control System

(2 Loop)

$-4184 \pm 844i$

$-1497 \pm 1086i$

-897

-179

-388

-365

$-202 \pm 24i$

$-297 \pm 83i$

The fact that all eigenvalues are negative means the original ADAS is stable. (Ref. 5:576). A listing of program EIGEN that solves for the eigenvalues and eigenvectors of $[A]$ is in Appendix C. Consult Ref. 7 for explanation of subroutine RGEIG used in computer program EIGEN.

V. Numerical Extent of the Problem

The baseline performance for ADAS using the Statement Of Work (SOW) disturbance is given in Table IV. These basleine figures will be used in comparsion to the worst case disurbance and also the results of any compensation.

As noted in the introduction, the worst case disturbance is called the CYCLE III disturbance. Since the angular errors are of a much greater concern than the translational disturbances, the CYCLE III

Table IV

Baseline Closed Loop Response
(input is ADAS SOW at Node #5)

Signal	Output (RMS)
A1 Torque Required	1.29 in-lb
A2 Torque Required	0.62 in-lb
Y-TRANS Error	4.16 in
ALPHA-P Error	1.71 rad

ROLL BASE MOTION PSD will be used. Due to the physical layout of the ADAS in the ALL, the roll base motion directly affects the angular control loops. Similarly, pitch base motion affects the translational control loops. It is for this reason that for a single input the worst case system output occurs when CYCLE III ROLL BASE MOTION PSD is input at the ALPHA-P disturbance point. The results of this worst case are listed in Table V.

Table V

Worst Case Closed Loop Response
(input is CYCLE III ROLL PSD at Node #5)

Signal	Output(RMS)
A1 Torque Required	4.73 in-lb
A2 Torque Required	2.74 in-lb
Y-TRANS Error	5.30 in
ALPHA-P Error	3.42 rad

Observe that for both the baseline and the worst case input, the torque-required-ratio of motors A1 and A2 is two to one (2:1). Under the CYCLE III Roll input this two for one torque demand exceeds the torque available for motor A1. This condition occurs due to the high frequency, large amplitude disturbances in the CYCLE III ROLL PSD.

Of equally great concern is the increase in ALPHA-P error over the baseline figure. The ALPHA-P error caused by the CYCLE III ROLL PSD (worst case is well over the specified limit, see Table II). Since these figures are derived from a linear simulation of ADAS, the actual system would have an even higher ALPHA-P error. This is because as the torque limits are exceeded the control system would saturate and the motors would no longer respond to correct for errors.

Documentation is also necessary in the form of ALPHA-P open loop response. The modification will directly affect the open loop response of the angular control loop. Therefore, it is important to know the response of the original system. This data is shown in Table VI.

Table VI

Open Loop Data for ALPHA-P Control Loop

	ALPHA-P
Gain Margin	+3.4 dB @ 920 Hz
Phase Margin	+22 degrees @ 725 Hz
0 dB Gain Crossover	725 Hz

The magnitude and phase angle plot is shown in Fig. 33. Since the open loop stability response is independent of the magnitude of disturbance input, there is no need for a baseline/worst case comparison.

The ALPHA-P open loop transfer function is defined as:

$$G(s) = \frac{\text{angular position of laser beam}}{\text{error in angular alignment of the laser beam}}$$

The error in angular alignment is measured at Node #5 in Fig. 7 and the angular position of the beam is Node (#8 + #4). The open loop response is measured this way to ensure unity feedback between Node (#8 + #4) and the disturbance/error summing point.

VI. Control System Modification and Predictions

Addition of Low Pass Filter

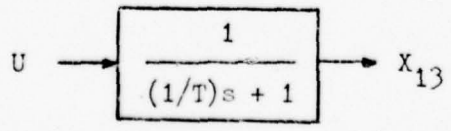
The control system is modified by placing a low pass filter in the electronic cross-coupling. In the frequency domain, this filter replaced the block labeled KA1AP (see Fig. 8) in the branch coming from the ALPHA-P control loop to the Y-TRANS control loop (Fig. 11). The filter is named GLOWPS, and is of the form:

$$\text{GLOWPS} = \frac{1.0}{(1/T)s + 1.0}$$

GLOWPS is essentially a filter with T as the cutoff frequency. A first order filter was chosen because of simplicity and the desire not to introduce more poles into the system than necessary.

The cutoff frequency T was varied between 0 and 700 Hz. Closed loop response data was calculated at each frequency to compare errors and required torques. Open loop data for the ALPHA-P loop will be gathered for stability considerations.

In the state space model the complimentary filter will add another state to the system. The state matrix $[A]$ will be of dimension 13X13 for the modified control system. Again the filter will replace the block labeled KA1AP. The state space representation of the filter is:



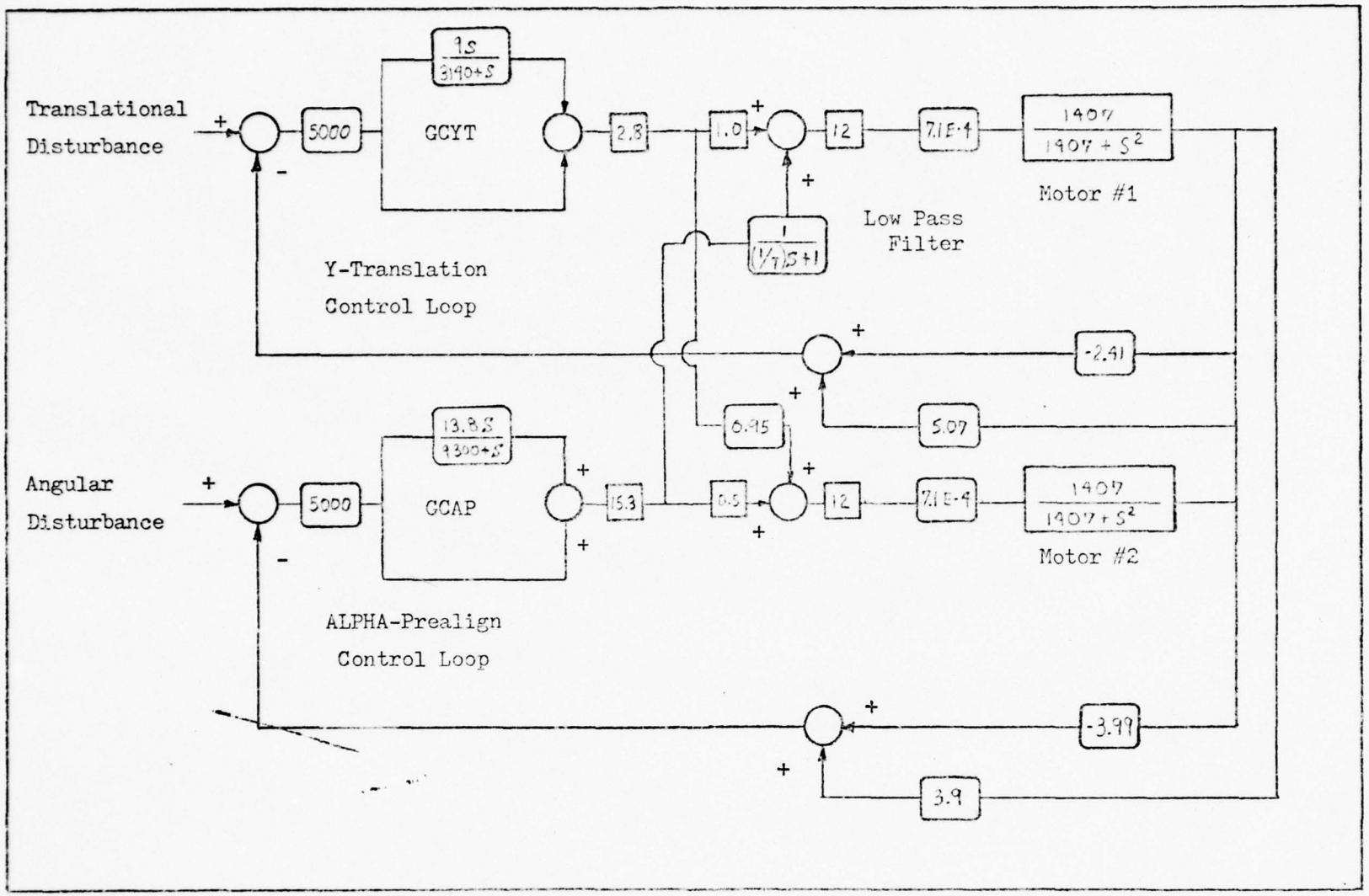


Fig.11. Modified ADAS Control System (Two Loop)

where

$$X_{13} = \left[-T\right] X_{13} + \left[T\right] U$$

substituting expression for U,

$$X_{13} = -(T)\ X_{13} - (T) \left[-4.4E{+}6\ X_1 + 4.51E{+}6\ X_3 + (15.3)\ X_6 + 1.13E{+}6\ X_9 \right]$$

The addition of state X_{13} also changes the X_2 equation. The form of X_2 equation for the modified control system is:

$$X_2 = -1407\ X_1 + 1407\ U$$

$$= -1407\ X_1 + (1407) \left[(12)\ \ (7.1E{-}4) \right] \left[(2.8C_1) + 12\ X_{13} \right]$$

$$= 4.03E{+}6\ X_1 - 8.5E{+}6\ X_3 + (33.6)\ X_5 + 1.68E{+}6\ X_7 + 12.0\ X_{13}$$

The full state matrix $\left[A\right]$ for the modified control system is Fig. 22 in Appendix C.

The function of this filter is to pass the low frequency content of the signal crossing from the ALPHA-P control loop to the Y-TRANS control loop and attenuate the higher frequency portion. Thus, the intent of the filter is to cut down on the torque requirement command of Motor #1. The big difference between the ADAS SOW and the CYCLE III roll disturbance is the large magnitude, high frequency error in CYCLE III roll. The filter will effectively reduce the CYCLE III

torque required signal to something similar to the ADAS SOW for Motor #1.

Reducing the Motor #1 torque will destroy the 2:1 mirror rotation for a pure angular error. Therefore, it is expected that translation error will increase with the addition of the filter. Since it is possible to correct for angular error with one to one movement of the mirrors, the angular error is not expected to increase. However, with the physical and electrical cross-coupling present, the direct effect on the angular error is not obvious.

VII. Results

The frequency domain closed loop response results with the complimentary filter in ADAS is shown in Table VII. The cutoff frequency is varied from 32 Hz to 700 Hz and the input is CYCLE III ROLL PSD at the ALPHA-P disturbance point.

Table VII

Comparison of Complimentary Filter Cutoff Frequencies

(Output in RMS; 1-SIGMA)

Cutoff Frequency (Hz)	A1 Torque Required (in-lb)	A2 Torque Required (in-lb)	ALPHA-P Error (rad)	Y-TRANS Error (rad)
32	1.90	2.27	1.75	6.20
56	1.71	2.26	1.90	6.42
64	1.65	2.25	1.95	6.49
111	1.25	2.22	2.33	6.87
143	1.00	2.20	2.64	7.09
150	0.96	2.19	2.71	7.13
190	0.88	2.18	3.14	7.34
200	0.92	2.18	3.25	7.39
350	2.93	2.49	4.90	7.56
700	14.80	8.49	11.30	8.90

This frequency domain closed loop data versus cutoff frequency is graphed in Fig.'s 12, 13, 14, and 15. On each of the four graphs the original system value is plotted as a dotted line for comparison. From the plot of Y-TRANS versus cutoff frequency, it is significant that for every frequency the modified system yields a higher value of error than the original system. This is as predicted. It was not predicted that the Y-TRANS error would increase with increasing cutoff frequency. This result did not seem likely due to the modification involved. As the cutoff frequency gets larger in a low pass filter, one would expect closer agreement with the original system.

This phenomena may also be observed in the ALPHA-P error graph. The low cutoff frequencies give the desired reduction in error (from the original system), but high cutoff frequencies give the reverse effect. From these two plots, one may see that the lowest cutoff frequency yields the least error. In fact, 0 Hz cutoff (no ALPHA-P $\longrightarrow$ Y-TRANS electronic coupling) would appear to be the best. Completely eliminating the ALPHA-P $\longrightarrow$ Y-TRANS electronic cross-coupling was not in the original plan, but the results are shown in Table VIII.

Table VIII

Closed Loop Response With No ALPHA-P $\longrightarrow$ Y-TRANS Electronic Cross-coupling

A1 Torque Required	A2 Torque Required	ALPHA-P Error	Y-TRANS Error
2.12 in-lb	2.28 in-lb	1.65 rad	5.86 in

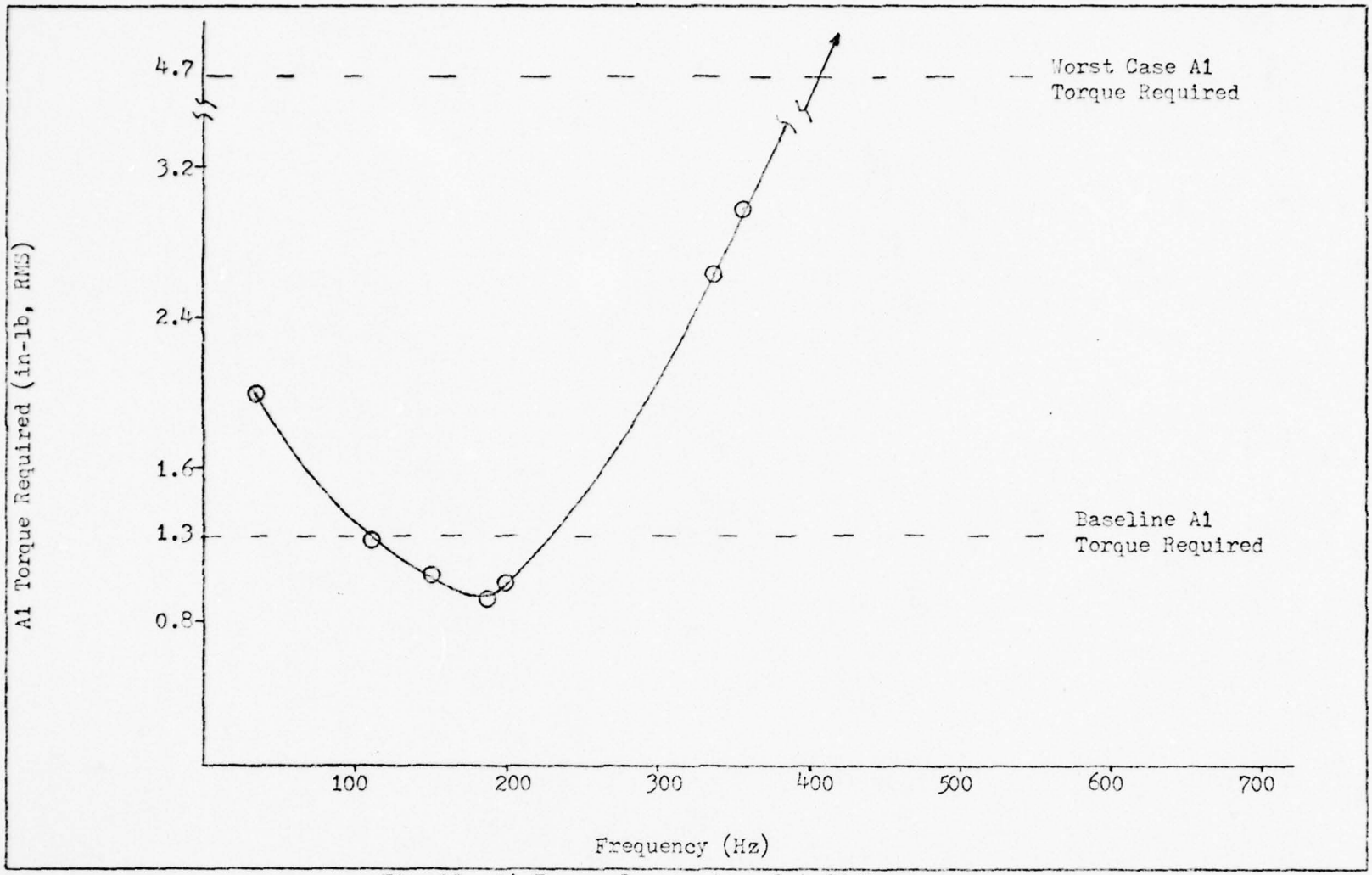


Fig. 12 . A1 Torque Required vs Cutoff Frequency

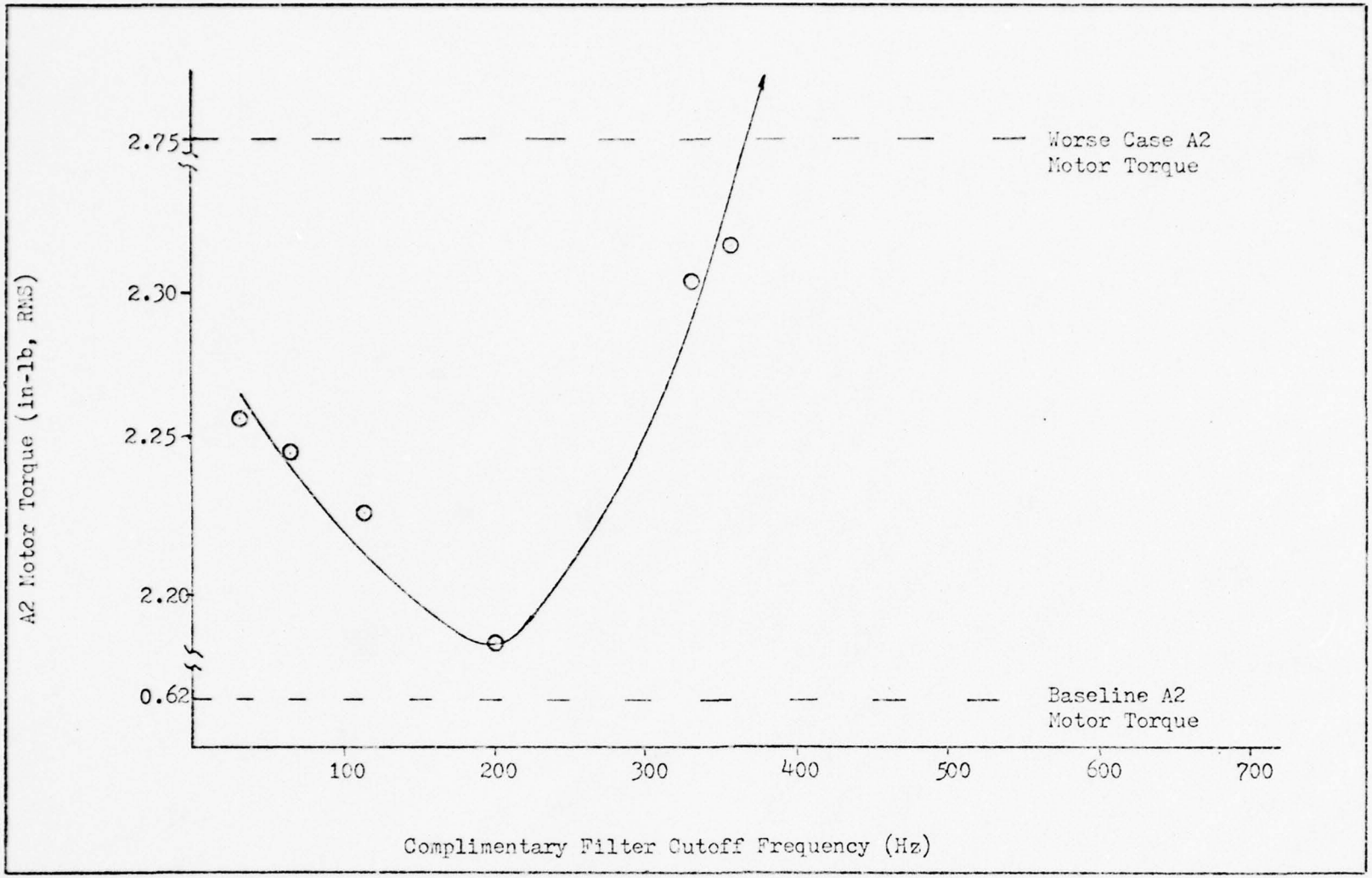


Fig.13. A2 Motor Torque Required vs Cutoff Frequency

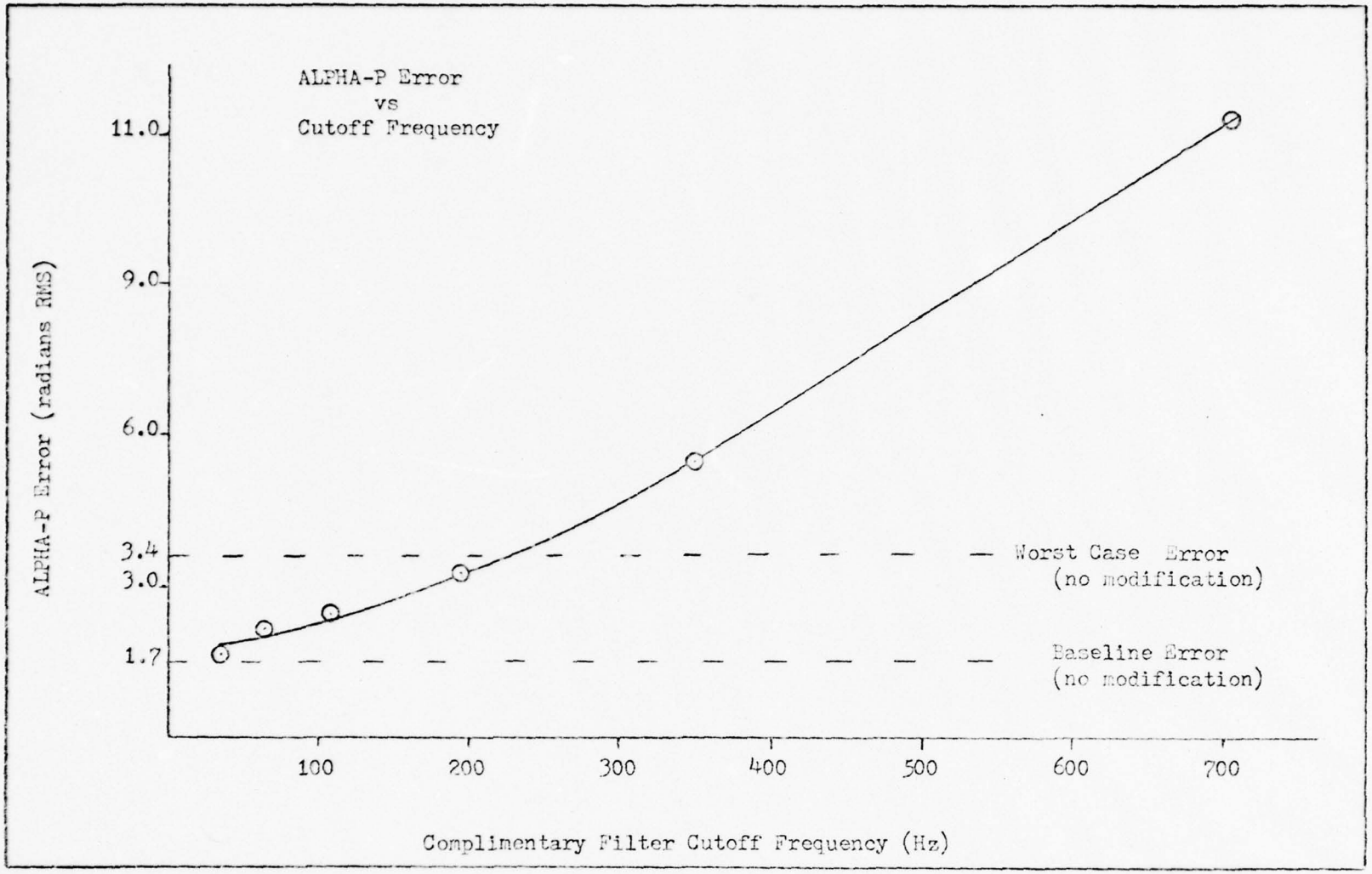


Fig.14 . ALPHA-P Error Signal vs Cutoff Frequency

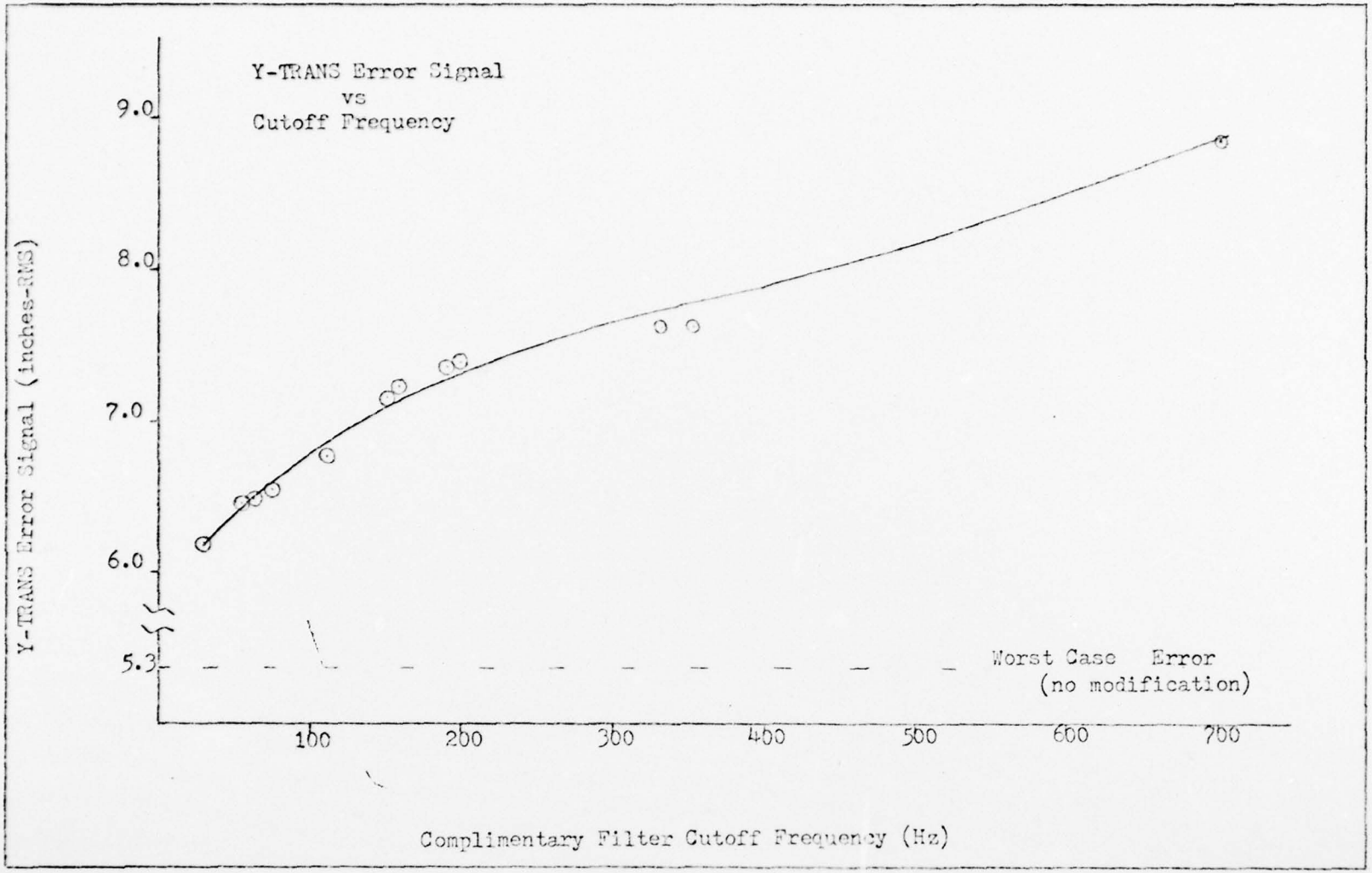


Fig.15. Y-TRANS Error Signal vs Cutoff Frequency

The A1 and A2 motor torque plots each yield a minimum at about 200 Hz. The A1 torque was considerably reduced as predicted. It was not expected that the A1 motor torque requirement would fall below that of the A2 motor.

The ALPHA-P open loop results are shown in Table IX on the next page. This table shows the increase in frequency response stability parameters from the original system to the system with no ALPHA-P $\longrightarrow$ Y-TRANS electronic cross-coupling. This result reinforces the data from the ALPHA-P and Y-TRANS error plots. The 190 → 200 Hz cutoff, which was the minimum region for the torque required curves yields an unstable open loop phase margin. ALPHA-P open loop error rejection curves for various cutoff frequencies shown in Appendix C.

The state space analysis results in a set of eigenvalues and associated eigenvectors. The system is considered stable if <u>all</u> the eigenvalues are negative. The results of the eigenvalue analysis are as follows:

1.) The 0 Hz cutoff frequency (no ALPHA-P $\longrightarrow$ Y-TRANS electronic coupling) produces a positive eigenvalue.

2.) It is not until the cutoff frequency is greater than 725 Hz that all eigenvalues become negative.

3.) The system does not appear to be well damped (Damping Ratio $\leq$ 0.707) until the cutoff frequency is moved past 5,000 Hz.

4.) At approximately 16,000 Hz cutoff frequency, the modified system eigenvalues are within 15% of the original system eigenvalues.

The exact numerical results are presented in Appendix C, Table XI.

As a result of the above eigenvalue information more frequency domain information was needed. This time the cutoff frequency was

Table IX

Comparison of ALPHA-P Open Loop Characteristics
with Various Filter Cutoff Frequencies

Cutoff Frequency (Hz)	0 dB Gain Crossover (Hz)	Phase Margin (degrees)	Gain Margin (dB)	
0	397	+45	+12	@ 918 Hz
32	397	+43	+9	@ 775 Hz
56	380	+40	+9	@ 775 Hz
64	400	+40	+9	@ 775 Hz
111	140	+150	+7.5	@ 725 Hz
150	460	-380		*
200	140	-351		*
330	550	+5	+2.1	@ 600 Hz
350	550	+5	+1.9	@ 600 Hz
700	652	0	+2.5	@ 623 Hz
Worst Case	725	+22	+3.4	@ 920 Hz

* Phase angle never equals -180 degrees below 10,000 Hz

varied from 800 to 16,000 Hz. The results are shown in Table X. More information concerning the erratic nature of the open loop response is shown in Fig.'s 29 - 32.

Table X

ADAS Two Loop Control System Response with Various Cutoff Frequencies

Cutoff Freq. (Hz)	Y-TRANS Error (inches)	ALPHA-P Error (radians)	A1 Motor Error (in-lb)	A2 Motor Torque (in-lb)	ALPHA-P Phase Margin (degrees)	ALPHA-P Gain Margin (dB)
800	75.0	11.0	16.0	8.8	-1 @ 650 Hz	+0.3 @ 650 Hz
1,100	31.0	5.8	8.1	4.1	+0 @ 675 Hz	0 @ 675 Hz
1,600	18.0	4.6	6.3	3.1	+0 @ 700 Hz	0 @ 700 Hz
4,000	8.1	3.8	5.2	2.5	+8 @ 775 Hz	+4 @ 880 Hz
8,000	6.1	3.6	4.9	2.4	+14 @ 775 Hz	+3 @ 880 Hz
12,000	5.7	3.5	4.9	2.4	+14 @ 775 Hz	+3 @ 880 Hz
16,000	5.6	3.5	4.8	2.4	+14 @ 775 Hz	+3 @ 880 Hz
Worst Case	5.3	3.4	4.7	2.75	+22 @ 725 Hz	+3 @ 918 Hz

VIII. Conclusions

Three types of basic analysis efforts were accomplished to analyze the performance of the proposed low pass filter compensator:

1.) Open loop frequency domain analysis

2.) Closed loop frequency domain analysis

3.) State space eigenvalue analysis

The conclusions of each approach are discussed separately and then the summary of the overall conclusions is presented.

Open Loop Frequency Domain Analysis

The ALPHA-P open loop transfer function is defined as follows:

$$G(s) = \frac{\text{angular position of laser beam}}{\text{error in angular alignment of laser beam}}$$

This is shown more clearly in Fig. 7. The error in angular alignment is Node #5 and the angular position of the beam Nodes (#8 + #4). The ALPHA-P open loop transfer function contains the ALPHA-P compensation and the dynamics from mirror-motors #1 and #2. The transfer function is defined this way to include the optical coupling between the two beam steering mirrors (see Appendix B) and the electronic decoupling from ALPHA-P to Y-TRANS loop. Since the open loop response is independent of input the modified system is compared to the original system independent of input angular disturbance. The open loop results of the original system are shown in Table VI and Fig. 33. This is the response when the block labeled KA1AP in Fig. 8 contain a constant gain equal to 1.0. To implement the low pass filter, KA1AP was reduced with $\frac{1.0}{(1/T)s + 1}$,

where T is the cutoff frequency. The cutoff frequency is varied from 0→16,000 Hz and the results are shown in Table IV, Table X and Fig.'s 29 - 32.

The conclusion is that the modified system improved the ALPHA-P open loop stability with cutoff frequencies below 100 Hz. With cutoff frequency above 100 Hz, the modified system actually decreased the stability of the control system. The gain and phase margins became very erratic as cutoff frequency increased. Although it is not clear, the fact that the ALPHA-P and Y-TRANS loops are no longer exactly decoupled may explain the instability. The poor stability data could be a result of the way the ALPHA-P open loop transfer function is defined. With the optical coupling and electronic decoupling between the two loops, straightforward frequency domain stability analysis is questionable if not impossible. For this reason, the accuracy of the improved stability figures at low cutoff frequencies must not be trusted. Clearly the stability analysis of the modified control system should not be done in the frequency domain.

Closed Loop Frequency Domain Analysis

Using the two loop ADAS control system shown in Fig. 7, the CYCLE III Roll angular disturbance PSD was input to the ALPHA-P control loop. The translational disturbance was kept equal to zero. The four main points for measuring the closed loop response were: the signal (torque command) to mirror-motors #1 and #2, and, the Y-TRANS and ALPHA-P error signals. The results of this simulation are shown in Table V and are called worst case figures. A first order low pass filter is substituted for block labeled KA1AP (see Fig. 8) and the

cutoff frequency was varied from 0 → 16,000 Hz. The closed loop results are presented in Tables VII, VIII, and X, and Fig.'s 12-15.

At low cutoff frequencies (below 200 Hz) the modified system closed loop response was greatly improved over the worst case. The torque requirements went down and the ALPHA-P error was reduced. The Y-TRANS error increased slightly but is still well within the limits of the system (see Table II). The torque requirements to the Beam Steering Mirror (BSM) #1 and #2 were minimized at about 200 Hz cutoff frequency. However, overall system response seemed best at very low or zero cutoff frequencies. The errors were at their lowest value with a zero Hz cutoff and the torque requirements to each BSM were well below their worst case values. Using a 0 Hz cutoff frequency resulted in an almost one-for-one mirror torque requirement. This means that both mirror-motors are being driven by exactly the same amount. There is no longer a two-for-one torque requirement between BSM #1 and BSM #2. This two-for-one torque requirement is undesirable because BSM #1 reaches its torque limit and the control system saturates. Table VII shows that the two-for-one torque requirement is reduced to one-to-one at the expense of increasing the Y-TRANS error. For 0 Hz cutoff, the Y-TRANS error is still well within the limit (see Table VIII and Table II).

However, as cutoff frequency is increased between 250 and 700 Hz, the ALPHA-P error exceeds the worst case error (see Fig. 14). Since the effect of the low pass filter decreases as the cutoff frequency increases, the result that the ALPHA-P error exceeded the worst case was unanticipated.

For cutoff frequencies between 800 and 16,000 Hz, the closed loop

response does approach the worst case figures. The problem is that the closed loop errors and torque approach the worst case figures from the high side. This means that, above 250 Hz cutoff frequency, the low pass filter does not provide any improvement in performance. Also, above about 700 Hz the modified system results are academic because the system response is not this high.

The conclusion from this closed loop frequency domain analysis is that the cutoff frequency must be below 250 Hz for the low pass filter to improve the performance of the system. In fact, from an error control standpoint, 0 Hz cutoff frequency seems to be the best. A low pass filter with 0 Hz cutoff frequency is the same as completely eliminating the electronic cross-coupling from the ALPHA-P to the Y-TRANS control loops. This conclusion supports the belief that the exact decoupling must be reduced or eliminated to reduce the torque saturation problem on BSM #1 and also control errors.

State Space Eigenvalue Analysis

The closed loop eigenvalues for the original and modified systems were calculated. The original system was characterized by 12 states (see ADAS State Space Model) and the addition of the first order low pass filter added an additional state. The eigenvalues were calculated from the closed loop system matrix $[A]$ using program EIGEN (listed in Appendix C) and subroutine RGEIG (Ref. 7).

Analysis of the original closed loop system yielded 12 eigenvalues with negative real parts (see Table III). This means that the original closed loop system is stable. (Ref. 5:576). The eigenvalues were then calculated for the modified control system with the low pass filter

cutoff frequency varied from 0 → 160,000 Hz. The first 7 eigenvalues for each case are shown in Table XI. The last 6 eigenvalues correspond to the 6 states of the disturbance shaping filters (see ADAS State Space Model). These 6 eigenvalues have no influence on the stability of the system so they are not shown.

The eigenvalues of the modified system show that it is unstable for cutoff frequencies below about 725 Hz. As the cutoff frequency is increased above 725 Hz the modified system eigenvalues approach the original system eigenvalues. The only difference is the presence of an eigenvalue corresponding to the low pass filter. As cutoff frequency is increased, the effect of this eigenvalue of the filter decreases. This result is as expected and corresponds to the declining effect of the low pass filter as cutoff frequency goes to infinity.

Since the open loop response of the control system is not greater than 725 Hz, any filter with cutoff frequency above 725 Hz would have no effect on the system. And since the modified system is always unstable at cutoff frequencies below 725 Hz, the low pass filter is not successful in improving the system.

Overall Conclusions

Combining the conclusions of the three analysis techniques, the overall conclusion is that the modified ADAS control system offers no improvement in performance over the original system. However, it is interesting to compare and contrast the results and conclusions of the frequency domain techniques with those of the state space analysis. Both the open and closed loop frequency domain results pointed to an improved stable modified system at low cutoff frequencies. The

eigenvalue analysis showed a large unstable closed loop pole at low cutoff frequencies. Thus, at low frequencies the two separate analysis techniques are in direct conflict. The real problem is then to decide which technique is giving correct results.

At high cutoff frequencies (200 → 800 Hz), there is less difference between frequency domain and state space analysis results. The eigenvalue analysis continues to show an unstable closed loop pole until cutoff frequency is higher than 725 Hz. This unstable pole could explain the erratic nature of the open loop stability figures. It could also explain the closed loop response figures exceeding the worst case figures. As a result, the state space approach seems to be the correct way to analyze the modified system. This modern control approach has become quite refined and is particularly suitable to multi-input, multi-output control system analysis.

IX. Recommendations

The ADAS control system is basically a multiple-input/multiple-output system. In the original ADAS control system design, a great deal of effort went into ensuring the angle and translation loops were completely decoupled electronically. Among other things, this allowed frequency domain techniques to be used in designing the compensation networks. If the vibrational environment was well defined and mirror-motors with infinite torque and acceleration capability were available, this technique would have worked. Since these things are not available some compromises must be made. The thrust of this study was to ignore the exact decoupling and decrease the torque/acceleration demand to motor #1. Since the translational errors are not as critical as the angular errors, more translational error would be accepted in order to decrease this torque/acceleration requirement.

However, as soon as the exact decoupling is altered, the limits of the frequency domain model are violated. It is no longer possible to assume single-input/single-output relationships. Since accepting more translational error and eliminating exact decoupling remains a viable solution, it is clear that another modeling and analysis technique is necessary.

It is recommended that modern state space control techniques be applied to this problem. A state space model of ADAS would be capable of handling multiple-inputs and multiple-outputs. Since a new model is recommended, it is further recommended that completely new feedback and compensation be designed. In this way the resulting

design would not be a modification to the original control system but a completely new design.

To illustrate this new design philosophy, a block diagram of the basic Airborne Dynamic Alignment System is shown in Fig. 16. Again the design will be performed on a two loop control system. In the final design the two basic two loop systems could be joined together for the full ADAS system. Note that there is no mirror angle feedback, electronic decoupling, or compensation network that appears in the present control system.

The open loop state matrix equations that describe the system are as follows;

$$\dot{\underline{X}}(t) = [A]\,\underline{X}(t) + [B]\,\underline{u}(t)$$

$$\underline{y} = [C]\,\underline{X}(t)$$

$$\underline{z} = [D]\,\underline{X}(t)$$

$$\underline{e} = \underline{d} - \underline{z}$$

where

$$[A] = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1407 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1407 & 0 \end{bmatrix}$$

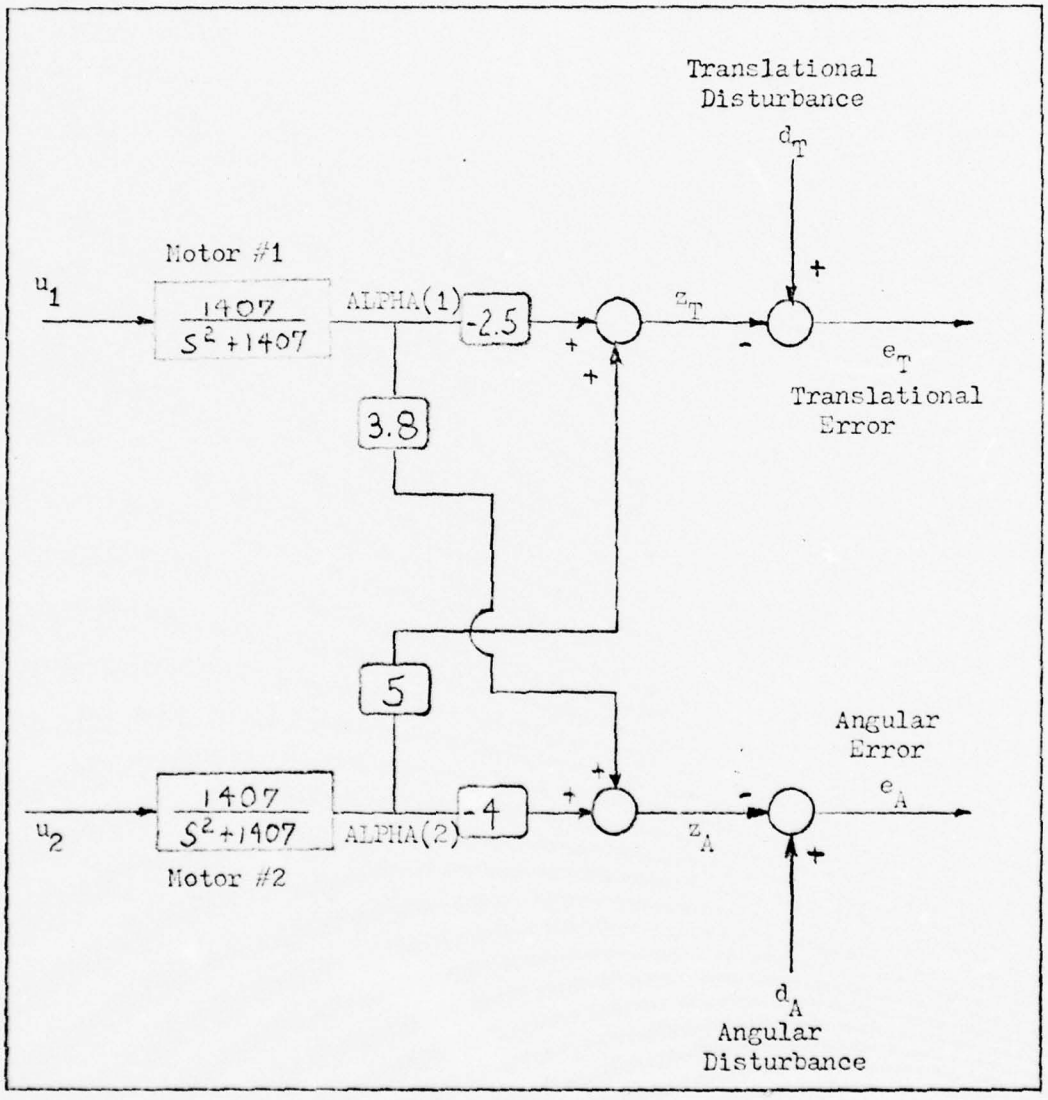


Fig.16. Block Diagram of Basic ADAS

$$\underline{X}(t) = \begin{bmatrix} X_1(t) \\ X_2(t) \\ X_3(t) \\ X_4(t) \end{bmatrix}$$

$$\underline{X}(t) = \begin{bmatrix} X_1(t), \text{ Angular Displacement of BSM \#1} \\ X_2(t), \text{ Rotational Velocity of BSM \#1} \\ X_3(t), \text{ Angular Displacement of BSM \#2} \\ X_4(t), \text{ Rotational Velocity of BSM \#2} \end{bmatrix}$$

$$[B] = \begin{bmatrix} 0 & 0 \\ 1407 & 0 \\ 0 & 0 \\ 0 & 1407 \end{bmatrix}$$

$$\underline{u}(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} \text{Command to Motor \#1} \\ \text{Command to Motor \#2} \end{bmatrix}$$

$$[C] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\underline{z}(t) = \begin{bmatrix} z_T(t) \\ z_A(t) \end{bmatrix} = \begin{bmatrix} \text{Translation of Beam} \\ \text{Angle of Beam} \end{bmatrix}$$

$$[D] = \begin{bmatrix} -2.5 & 0 & 5 & 0 \\ 3.8 & 0 & -4 & 0 \end{bmatrix}$$

$$\underline{e}(t) = \begin{bmatrix} e_T(t) \\ e_A(t) \end{bmatrix} = \begin{bmatrix} \text{Trans Error of Beam} \\ \text{Angle Error of Beam} \end{bmatrix}$$

$$\underline{d}(t) = \begin{bmatrix} d_T(t) \\ d_A(t) \end{bmatrix} = \begin{bmatrix} \text{Translational Disturbance of Beam} \\ \text{Angular Disturbance of Beam} \end{bmatrix}$$

When this basic system is shown in a state matrix diagram, it is easily identified as a basic tracking problem. This state matrix diagram is in Fig. 17. The significance of identifying this basic tracking problem is that there are several systematic ways available of solving this problem. (Ref. 1:253).

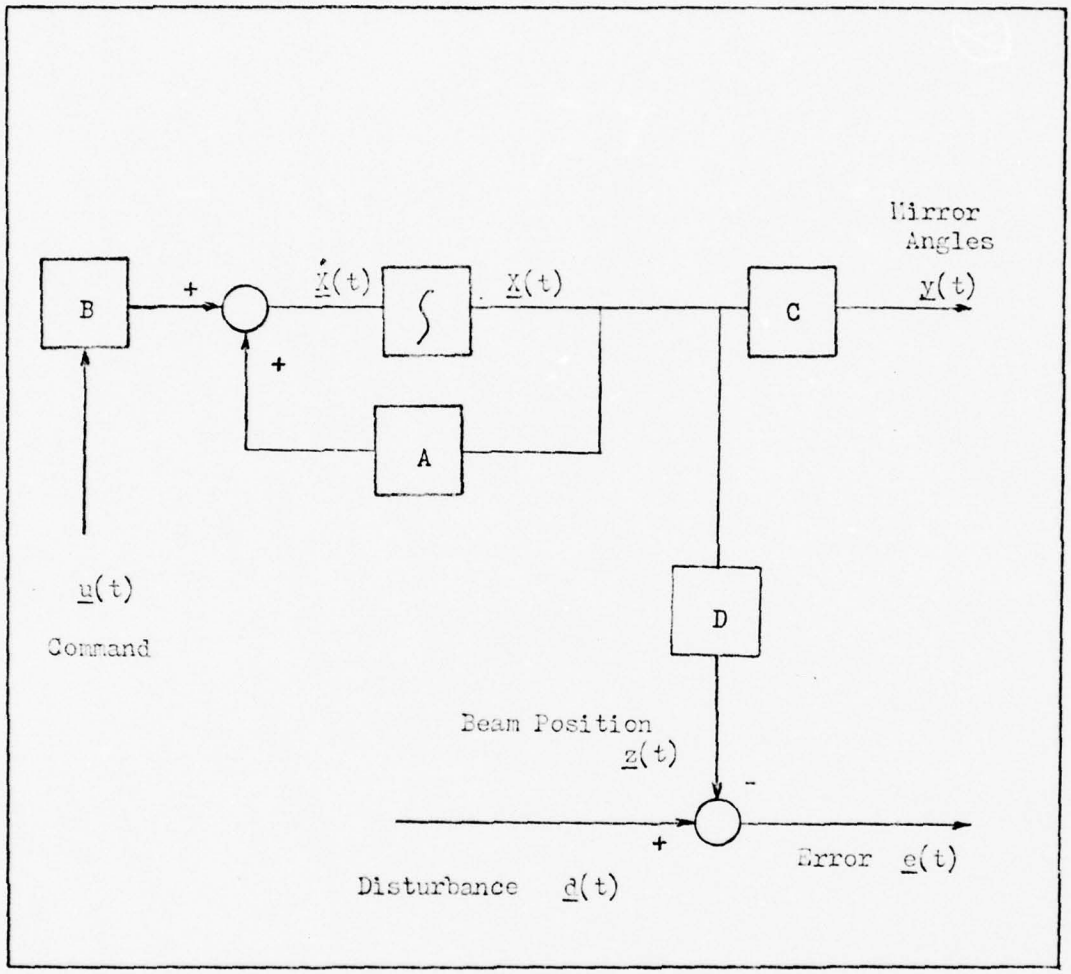


Fig.17. Basic ADAS Tracking Problem

With the insight gained from conducting the previous study of ADAS in the frequency domain, the following is an outline of the solution approach for the state space ADAS tracking problem;

1.) Improve "open loop" mirror-motor damping by feeding the states ($\underline{X}(t)$) through a matrix $[F_x]$ to the input $u(t)$.

2.) Improve overall system closed loop response by feedback of the disturbance through a matrix $[F_d]$ to the input u(t).

When the states are fed back through matrix $[F_x]$, the control u(t) becomes;

$$\underline{u}(t) = [F_x]\,\underline{X}(t)$$

substituting u(t) into the $\underline{X}(t)$ equation:

$$\underline{\dot{X}}(t) = [A]\,\underline{X}(t) + [B][F_x]\,\underline{X}(t)$$

$$= [A + BF_x]\,\underline{X}(t)$$

Thus, $[A + BF_x]$ becomes the new matrix that defines the closed loop response between $\underline{u}(t)$ and $\underline{X}(t)$. Now, with the proper choice of the state feedback matrix $[F_x]$ the closed loop eigenvalues may be changed to improve the damping of the system. (Ref. 8).

When the disturbance ($\underline{d}(t)$) is fed back to the input ($\underline{u}(t)$) with the revised open loop system the control system will respond to correct any input disturbance. The new closed loop system equation is now:

$$\underline{\dot{X}}(t) = [A + BF_x]\,\underline{X}(t) + [B][F_d]\,\underline{d}(t)$$

It is through this $[F_d]$ matrix that the relative inportance of the translational and angular errors may be specified. Since the angular error is of greater importance, $[F_d]$ may be designed with a heavier weighting on angular errors. The best way to design $[F_d]$ is through linear optimal control theory. A cost function (J) would be defined to make angular error control more important than

translational error control. The cost function (J) is also the place to define the weighting of the controls u_1 and u_2.

The only problem in implementing the above recommendations is that two of the states (X_2 and X_4) and both disturbances $d_T(t)$ and $d_A(t)$ are not directly available. Again, modern control theory provides a solution to this dilemma. Since two of the states X_1 and X_3 are available through output $\underline{y}(t)$, an observer may be used to estimate the states X_2 and X_4. All four states may then be fed back through $\left[\underline{F}_x\right]$ to improve the system damping. The disturbances ($\underline{d}(t)$) are also estimated using a Kalman filter. (Ref. 1:341). The Kalman filter used the errors that are available from the sensors and the states from the observer to estimate $\underline{d}(t)$. Finally $\underline{d}(t)$ is multiplied by $\left[\underline{F}_d\right]$ and fed into the control $\underline{u}(t)$. The state matrix of the total system is shown in Fig. 18.

Several more details need to be examined before the control system shown in Fig. 18 will work properly. These include: picking actual eigenvalues to give the desired closed loop response, and determination of weighting matricies on $e_T(t)$, $e_A(t)$, $u_1(t)$, and $u_2(t)$. Additionally, the observer and Kalman filter would need to be "fine tuned" for optimal estimates of the states and disturbances. A computer probram would have to be designed to simulate this new control system. It would then be through simulation of the system that these details could be worked out. Such a design approach is felt to be advantageous because it is inherently capable of dealing with the multi-input and multi-output system. For this particular system, it does not appear beneficial to exactly decouple and treat as two single-input/single-output system designs.

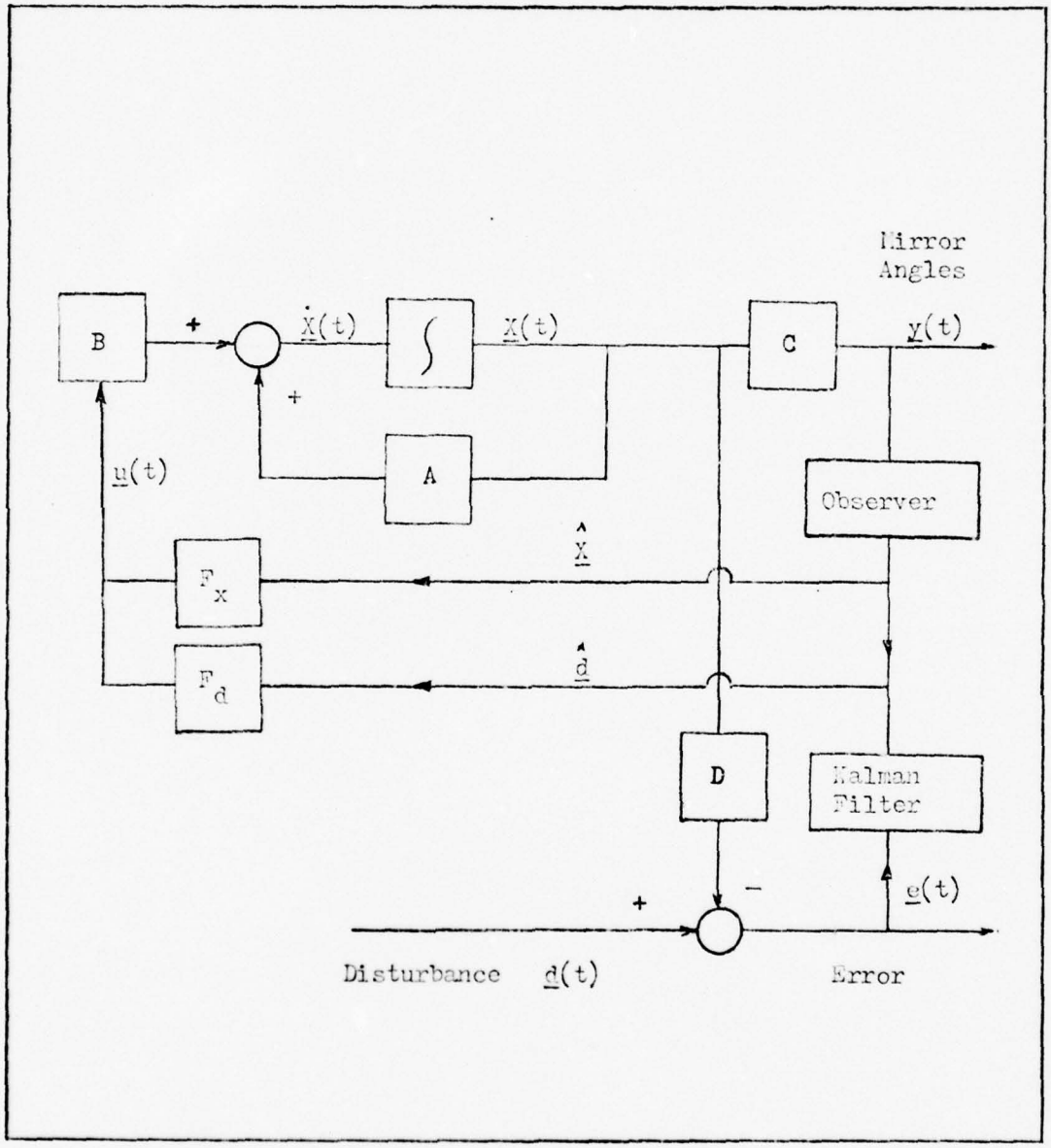


Fig.18. Optimal ADAS Tracking Problem

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Appendix A

Frequency Domain Computer Program

ADAS is modeled in the frequency domain through a general purpose frequency domain program called "FRQRSP." The total program consists of 22 subroutines and a small main program. The function of the main program (FRQPGM) is to initialize the run and call the main subroutine "FRQRSP." The calling sequence is shown below.

(1)	(2)	(3)	(4)	(5)	(6)
FRQRSP					
	FIRST				
	FUNCTIONG				
	GET				
	LAST				
	FUNCTIONPSD				
		PRINT			
	SAVE				
	SOLVER				
		COEF			
			COEFADS		
				CONADS	
			COEFAPT		BLOCKADAS
				CONAPT	
			COEFAAS		BLOCKAPT
				CONAAS	
		SIEDEL			
		SPARSE			
	PIVSEL				
	STEP				
	FRPLOT				

Subroutines; FRQRSP, SAVE, GET, SOLVER, SPARSE, PIVSEL, SIEDEL, FRPLOT, STEP, and PRINT belong to the general purpose package.

Subroutines; COEF, COEFADS, CONADS, BLOCKADAS, COEFAPT, CONAPT, BLOCKAPT, COEFAAS, CONAAS, and FUNCTIONG are used to describe the APT, AAS, and ADAS subsystems to the ALL. All of these subroutines were retained in the simulation during this study to facilitate later total system integration. COEFADS, CONADS, BLOCKADAS, and FUNCTIONG are the only subroutines that were altered for the ADAS control system modification. These subroutines are listed at the end of this appendix. The "FRQRSP USER GUIDE", (Ref. 3) contains a detailed description of the rest of the subroutines. It also gives the user the information necessary to adapt FRQRSP to any particular problem.

Output is in tabular and graphical form. Frequency is in both radians per second and Hertz. Amplitude is in magnitude of G(s) and decibels, where one decibel equals 20 $\text{Log}_{10} | \text{MAG}(G) |$. The phase of G(s) is tabulated in degrees as the imaginary part of G(s). Also, phase is corrected to account for phase beyond $\pm$ 180 degrees.

```
      BLOCK DATA ADAS                                                    BLOCKADAS   2
C                                                                        BLOCKADAS   3
      REAL KZT,KBP,KB1,KB2,KYT,KAP,KA1,KA2,KB1ZT,KB2ZT,                  BLOCKADAS   4
     1     KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP                          BLOCKADAS   5
      COMPLEX GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,            BLOCKADAS   6
     1 GFB2,GAB2,GMB2,GLB21,GLB22,GELZT,GELBP,GMLB1,GMLB2,               BLOCKADAS   7
     2GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                              BLOCKADAS   8
     3  GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                           BLOCKADAS   9
     4    GELYT,GELAP,GMLA1,GMLA2,GBSMOD,GLOWPS                         COMPFIL2   12
C                                                                        BLOCKADAS  11
C                                                                        BLOCKADAS  12
      COMMON/ALL/P(150),NR,NW,ISTART,METHOD                              BLOCKADAS  13
      COMMON /CADAS/ SYTAA,SAPAA,SZTAA,SBPAA,SYTBA,SAPBA,SZTBA,SBPBA,    BLOCKADAS  14
     1               YT,AP,ZT,BP,KYT,KAP,KA1,KA2,KZT,KBP,KB1,KB2,       BLOCKADAS  15
     2               YTCW2,YTCW1,APCW2,APCW1,ZTCW2,ZTCW1,BPCW2,BPCW1,    BLOCKADAS  16
     3               YTSGAN,APSGAN,A1MFRQ,A2MFRQ,                       BLOCKADAS  17
     4               ZTSGAN,BPSGAN,B1MFRQ,B2MFRQ,                       BLOCKADAS  18
     5               A1LSF,A2LSF,B1LSF,B2LSF,                           BLOCKADAS  19
     7               WFYT,ZFYT,WFAP,ZFAP,WFA1,ZFA1,WFA2,ZFA2,           BLOCKADAS  20
     8               WLA11,ZLA11,WLA12,ZLA12,WLA21,ZLA21,WLA22,ZLA22,   BLOCKADAS  21
     9               WFZT,ZFZT,WFBP,ZFBP,WFB1,ZFB1,WFB2,ZFB2,           BLOCKADAS  22
     A               WLB11,ZLB11,WLB12,ZLB12,WLB21,ZLB21,WLB22,ZLB22,   BLOCKADAS  23
     B               SYTA1,SYTA2,SYTB1,SYTB2,SAPA1,SAPA2,SAPB1,SAPB2,   BLOCKADAS  24
     C               SZTA1,SZTA2,SZTB1,SZTB2,SBPA1,SBPA2,SBPB1,SBPB2,   BLOCKADAS  25
     D               KB1ZT,KB2ZT,KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP,   BLOCKADAS  26
     E               SYTGA,SAPGA,SZTGA,SBPGA                            BLOCKADAS  27
      COMMON /GADAS/ GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,     BLOCKADAS  28
     1               GFB2,GAB2,GMB2,GLB21,GLB22,GELZT,GELBP,GMLB1,GMLB2, BLOCKADAS  29
     2               GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,              BLOCKADAS  30
     3               GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,              BLOCKADAS  31
     4               GELYT,GELAP,GMLA1,GMLA2,GBSMOD,GLOWPS              COMPFIL2   13
C                                                                        BLOCKADAS  33
```

```
C                                                                       BLOCKADAS  34
      DATA SYTAA,SAPAA,SZTAA,SBPAA/0.56,.1611,0.0,0.0/                  FIRST      115
      DATA SYTBA,SAPBA,SZTBA,SBPBA/-5.03,-1.9935,0.0,0.0/               FIRST      117
      DATA  KYT,KAP,KA1,KA2/2.78,15.3,12.0,12.0/                        BLOCKADAS  37
      DATA  KZT,KBP,KB1,KB2/2.78,15.3,12.0,12.0/                        BLOCKADAS  38
      DATA  YTCW2,YTCW1,APCW2,APCW1/3140.,314.,9300.,630./              BLOCKADAS  39
      DATA  ZTCW2,ZTCW1,BPCW2,BPCW1/3140.,314.,9300.,630./              BLOCKADAS  40
      DATA  YTSGAN,APSGAN,A1MERO,A2MERO/5000.,5000.,10000.,10000./      BLOCKADAS  41
      DATA  ZTSGAN,BPSGAN,B1MERO,B2MERO/5000.,5000.,10000.,10000./      BLOCKADAS  42
      DATA A1LSF,A2LSF,B1LSF,B2LSF/4*7.1E-4/                            BLOCKADAS  43
      DATA  WFYT,ZFYT,WFAP,ZFAP/12560.,1.414,12560.,1.414/              BLOCKADAS  44
      DATA  WFA1,ZFA1,WFA2,ZFA2/15080.,0.003,15080.,0.003/              BLOCKADAS  45
      DATA  WLA11,ZLA11,WLA12,ZLA12/37.51,0.0,15080.,0.003/             BLOCKADAS  46
      DATA  WLA21,ZLA21,WLA22,ZLA22/37.51,0.0,15080.,0.003/             BLOCKADAS  47
      DATA  WFZT,ZFZT,WFBP,ZFBP/12560.,1.414,12560.,1.414/              BLOCKADAS  48
      DATA  WFB1,ZFB1,WFB2,ZFB2/15080.,0.003,15080.,0.003/              BLOCKADAS  49
      DATA  WLB11,ZLB11,WLB12,ZLB12/37.51,0.0,15080.,0.003/             BLOCKADAS  50
      DATA  WLB21,ZLB21,WLB22,ZLB22/37.51,0.0,15080.,0.003/             BLOCKADAS  51
      DATA SYTA1,SYTA2,SYTB1,SYTB2/-2.42,5.07,0.0,0.0/                  PROVEIT     5
      DATA SAPA1,SAPA2,SAPB1,SAPB2/3.859,-3.996,0.0,0.0/                PROVEIT     6
      DATA SZTA1,SZTA2,SZTB1,SZTB2/0.0,0.0,0.0,0.0/                     PROVEIT     7
      DATA SBPA1,SBPA2,SBPB1,SBPB2/0.0,0.0,0.0,0.0/                     PROVEIT     8
C                                                                       PROVEIT     9
      DATA  KB1ZT,KB2ZT,KB1BP,KB2BP/1.0,-1.0,1.0,-.498/                 BLOCKADAS  56
      DATA KA1YT,KA2YT,KA1AP,KA2AP/1.0,.95,0.00497,.5/                  COMPFIL2   15
C                                                                       COMPFIL2   16
      DATA  SYTGA,SAPGA,SZTGA,SBPGA/-.09,0.0,.03,0.0/                   BLOCKADAS  58
C                                                                       BLOCKADAS  59
      END                                                               BLOCKADAS  60
```

```
      SUBROUTINE CONADS(S,N)                                                CONADS     2
C                                                                           CONADS     3
C                                                                           CONADS     4
      COMPLEX GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,               CONADS     5
     1 GFB2,GAB2,GMB2,GLB21,GLB22,GELZT,GELBP,GMLB1,GMLB2,                  CONADS     6
     2GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                                 CONADS     7
     3  GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                              CONADS     8
     4                GELYT,GELAP,GMLA1,GMLA2,GBSMOD,GLOWPS                 COMPFIL2   9
C                                                                           CONADS    10
      COMPLEX    S                                                          CONADS    11
C                                                                           CONADS    12
      REAL KZT,KBP,KB1,KB2,KYT,KAP,KA1,KA2,KB1ZT,KB2ZT,                     CONADS    13
     1     KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP                              CONADS    14
C                                                                           CONADS    15
      COMMON/ALL/P(150),NR,NW,ISTART,METHOD                                 CONADS    16
      COMMON /CADAS/ SYTAA,SAPAA,SZTAA,SBPAA,SYTBA,SAPBA,SZTBA,SBPBA,       CONADS    17
     1               YT,AP,ZT,BP,KYT,KAP,KA1,KA2,KZT,KBP,KB1,KB2,          CONADS    18
     2               YTCW2,YTCW1,APCW2,APCW1,ZTCW2,ZTCW1,BPCW2,BPCW1,       CONADS    19
     3               YTSGAN,APSGAN,A1MERO,A2MERO,                           CONADS    20
     4               ZTSGAN,BPSGAN,B1MERO,B2MERO,                           CONADS    21
     5               A1LSE,A2LSE,B1LSE,B2LSE,                               CONADS    22
     7               WFYT,ZFYT,WFAP,ZFAP,WFA1,ZFA1,WFA2,ZFA2,               CONADS    23
     8               WLA11,ZLA11,WLA12,ZLA12,WLA21,ZLA21,WLA22,ZLA22,       CONADS    24
     9               WFZT,ZFZT,WFBP,ZFBP,WFB1,ZFB1,WFB2,ZFB2,               CONADS    25
     A               WLB11,ZLB11,WLB12,ZLB12,WLB21,ZLB21,WLB22,ZLB22,       CONADS    26
     B               SYTA1,SYTA2,SYTB1,SYTB2,SAPA1,SAPA2,SAPB1,SAPB2,       CONADS    27
     C               SZTA1,SZTA2,SZTB1,SZTB2,SBPA1,SBPA2,SBPB1,SBPB2,       CONADS    28
     D               KB1ZT,KB2ZT,KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP,       CONADS    29
     E               SYTGA,SAPGA,SZTGA,SBPGA                                CONADS    30
```

```
      COMMON /GADAS/ GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,      CONADS     31
     1               GFB2,GAB2,GMB2,GLB21,GLB22,GELZT,GELBP,GMLB1,GMLB2,  CONADS     32
     2               GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                CONADS     33
     3               GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                CONADS     34
     4               GELYT,GFLAP,GMLA1,GMLA2,GBSMOD,GLOWPS                COMPFIL2   10
C                                                                         CONADS     36
C                                                                         CONADS     37
      GLOWPS=1.0/(KA1AP*S+1.0)                                            COMPFIL2   11
      GBSMOD=(1.0+2.9E-7*S+7.5E-9*S*S)/(1.0+1.83E-7*S+3.0E-9*S*S)         CONADS     38
      GFZT=1.0/((S/WFZT)**2+ZFZT*(S/WFZT)+1.0)                            CONADS     39
      GCZT=1.0+(ZTCW2/ZTCW1-1.0)*S/(S+ZTCW2)                              CONADS     40
      GFB1=(1.+(S/WFB1)**2)/((S/WFB1)**2+ZFB1*(S/WFB1)+1.0)               CONADS     41
      GAB1=2.*B1MFRQ/(S+B1MFRQ)                                           CONADS     42
      GMB1=GAB1/(1.+GAB1)                                                 CONADS     43
      GLB11=1.0/((S/WLB11)**2+ZLB11*(S/WLB11)+1.0)                        CONADS     44
      GLB12=1.0/((S/WLB12)**2+ZLB12*(S/WLB12)+1.0)                        CONADS     45
      GFBP=1.0/((S/WFBP)**2+ZFBP*(S/WFBP)+1.0)                            CONADS     46
      GCBP=1.0+(BPCW2/BPCW1-1.0)*S/(S+BPCW2)                              CONADS     47
      GFB2=(1.0+(S/WFB2)**2)/((S/WFB2)**2+ZFB2*(S/WFB2)+1.0)              CONADS     48
      GAB2=2.*B2MFRQ/(S+B2MFRQ)                                           CONADS     49
      GMB2=GAB2/(1.+GAB2)                                                 CONADS     50
      GLB21=1.0/((S/WLB21)**2+ZLB21*(S/WLB21)+1.0)                        CONADS     51
      GLB22=1.0/((S/WLB22)**2+ZLB22*(S/WLB22)+1.0)                        CONADS     52
      GELZT=ZTSGAN*GFZT*GCZT*KZT                                          CONADS     53
      GELBP=BPSGAN*GFBP*GCBP*KBP                                          CONADS     54
      GMLB1=KB1*GFB1*GMB1*B1LSF*GLB11*GLB12*GBSMOD                        CONADS     55
      GMLB2=KB2*GFB2*GMB2*B2LSF*GLB21*GLB22*GBSMOD                        CONADS     56
      GFYT=1.0/((S/WFYT)**2+ZFYT*(S/WFYT)+1.0)                            CONADS     57
```

```
      GCYT=1.0+(YTCW2/YTCW1-1.0)*S/(S+YTCW2)                                  CONADS     58
      GFA1=(1.+(S/WFA1)**2)/((S/WFA1)**2+ZFA1*(S/WFA1)+1.0)                   CONADS     59
      GAA1=2.0*A1MERO/(S+A1MERO)                                              CONADS     60
      GMA1=GAA1/(1.+GAA1)                                                     CONADS     61
      GLA11=1.0/((S/WLA11)**2+ZLA11*(S/WLA11)+1.0)                            CONADS     62
      GLA12=1.0/((S/WLA12)**2+ZLA12*(S/WLA12)+1.0)                            CONADS     63
      GFAP=1.0/((S/WFAP)**2+ZFAP*(S/WFAP)+1.0)                                CONADS     64
      GCAP=1.0+(APCW2/APCW1-1.0)*S/(S+APCW2)                                  CONADS     65
      GFA2=(1.0+(S/WFA2)**2)/((S/WFA2)**2+ZFA2*(S/WFA2)+1.0)                  CONADS     66
      GAA2=2.0*A2MERO/(S+A2MERO)                                              CONADS     67
      GMA2=GAA2/(1.+GAA2)                                                     CONADS     68
      GLA21=1.0/((S/WLA21)**2+ZLA21*(S/WLA21)+1.0)                            CONADS     69
      GLA22=1.0/((S/WLA22)**2+ZLA22*(S/WLA22)+1.0)                            CONADS     70
      GELYT=YTSGAN*GFYT*GCYT*KYT                                              CONADS     71
      GELAP=APSGAN*GFAP*GCAP*KAP                                              CONADS     72
      GMLA1=KA1*GFA1*GMA1*A1LSF*GLA11*GLA12*GRSMOD                            CONADS     73
      GMLA2=KA2*GFA2*GMA2*A2LSF*GLA21*GLA22*GRSMOD                            CONADS     74
C                                                                             CONADS     75
      RETURN                                                                  CONADS     76
      END                                                                     CONADS     77
```

```
      SUBROUTINE COEFADS(A,B,ICOL,NEQN,NROW,NCOL,S,N,R,NADS)                COEFADS    2
C                                                                           COEFADS    3
C                                                                           COEFADS    4
C     THIS SUBROUTINE FOR TWO CHANNEL                                       COEFADS    5
C     COUPLED ADAS SYSTEM.  WRITTEN BY MERRITT                              COEFADS    6
C     USING MATRIX FROM COREY.  5 JAN 77.                                   COEFADS    7
      COMPLEX GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,               COEFADS    8
     1 GFB2,GAB2,GMB2,GLB21,GLB22,GELZT,GELBP,GMLB1,GMLB2,                  COEFADS    9
     2GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                                 COEFADS   10
     3  GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                               COEFADS   11
     4    GELYT,GELAP,GMLA1,GMLA2,GRSMOD,GLOWPS                            COMPFIL2   6
C                                                                           COEFADS   13
      COMPLEX A,B,S,P                                                       COEFADS   14
      REAL P                                                                COEFADS   15
      REAL KZT,KBP,KB1,KB2,KYT,KAP,KA1,KA2,KB1ZT,KB2ZT,                     COEFADS   16
     1     KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP                              COEFADS   17
C                                                                           COEFADS   18
      COMMON/ALL/P(150),NR,NW,ISTART,METHOD                                 COEFADS   19
      COMMON /CADAS/ SYTAA,SAPAA,SZTAA,SBPAA,SYTBA,SAPBA,SZTBA,SBPBA,       COEFADS   20
     1               YT,AP,ZT,BP,KYT,KAP,KA1,KA2,KZT,KBP,KB1,KB2,          COEFADS   21
     2               YTCW2,YTCW1,APCW2,APCW1,ZTCW2,ZTCW1,BPCW2,BPCW1,       COEFADS   22
     3               YTSGAN,APSGAN,A1MERO,A2MERO,                          COEFADS   23
     4               ZTSGAN,BPSGAN,B1MERO,B2MERO,                          COEFADS   24
     5               A1LSE,A2LSE,B1LSE,B2LSE,                              COEFADS   25
     7               WFYT,ZFYT,WFAP,ZFAP,WFA1,ZFA1,WFA2,ZFA2,              COEFADS   26
     8               WLA11,ZLA11,WLA12,ZLA12,WLA21,ZLA21,WLA22,ZLA22,      COEFADS   27
     9               WFZT,ZFZT,WFBP,ZFBP,WFB1,ZFB1,WFB2,ZFB2,              COEFADS   28
     A               WLB11,ZLB11,WLB12,ZLB12,WLB21,ZLB21,WLB22,ZLB22,      COEFADS   29
     B               SYTA1,SYTA2,SYTB1,SYTB2,SAPA1,SAPA2,SAPB1,SAPB2,      COEFADS   30
     C               SZTA1,SZTA2,SZTB1,SZTB2,SBPA1,SBPA2,SBPB1,SBPB2,      COEFADS   31
     D               KB1ZT,KB2ZT,KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP,      COEFADS   32
     E               SYTGA,SAPGA,SZTGA,SBPGA                               COEFADS   33
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      COMMON /GADAS/ GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GF3P,GC3P,      COEFADS    34
     1               GFB2,GAB2,GMB2,GLB21,GLB22,GELZT,GEL3P,GML31,GML32,  COEFADS    35
     2               GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                COEFADS    36
     3               GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                COEFADS    37
     4               GELYT,GELAP,GML41,GML42,GBSMOD,GLOWPS                COMPFIL2    7
C                                                                         COEFADS    39
C                                                                         COEFADS    40
C                                                                         COEFADS    41
      DIMENSION A(NROW,NCOL), B(NROW), ICOL(NROW,NCOL), R(NROW)           COEFADS    42
C                                                                         COEFADS    43
      CALL CONADS(S,N)                                                    COEFADS    44
C                                                                         COEFADS    45
C                                                                         COEFADS    46
      A(NADS+1,1)=1.  $ ICOL(NADS+1,1)=NADS+1                             COEFADS    47
      A(NADS+1,2)=-SYTA1  $ ICOL(NADS+1,2)=NADS+4                         COEFADS    48
      A(NADS+1,3)=-SYTA2  $ ICOL(NADS+1,3)=NADS+8                         COEFADS    49
      A(NADS+1,4)=-SYTB1  $ ICOL(NADS+1,4)=NADS+12                        COEFADS    50
      A(NADS+1,5)=-SYTB2  $ ICOL(NADS+1,5)=NADS+16                        COEFADS    51
C                                                                         COEFADS    52
      A(NADS+2,1)=GELYT  $ ICOL (NADS+2,1)=NADS+1                         COEFADS    53
      A(NADS+2,2)=1.  $ ICOL(NADS+2,2)=NADS+2                             COEFADS    54
C                                                                         COEFADS    55
      A(NADS+3,1)=-KA1YT  $ ICOL(NADS+3,1)=NADS+2                         COEFADS    56
      A(NADS+3,2)=1.   $ ICOL(NADS+3,2)=NADS+3                            COEFADS    57
      A(NADS+3,3)=-GLOWPS  $ICOL(NADS+3,3)=NADS+6                         COMPFIL2    8
C                                                                         COEFADS    59
      A(NADS+4,1)=-GML41  $ ICOL(NADS+4,1)=NADS+3                         COEFADS    60
      A(NADS+4,2)=1.  $ ICOL(NADS+4,2)=NADS+4                             COEFADS    61
C                                                                         COEFADS    62
      A(NADS+5,1)=-SAPA1  $ ICOL(NADS+5,1)=NADS+4                         COEFADS    63
      A(NADS+5,2)=1.  $ ICOL(NADS+5,2)=NADS+5                             COEFADS    64
      A(NADS+5,3)=-SAPA2  $ ICOL(NADS+5,3)=NADS+8                         COEFADS    65
      A(NADS+5,4)=-SAPB1  $ ICOL(NADS+5,4)=NADS+12                        COEFADS    66
      A(NADS+5,5)=-SAPB2  $ ICOL(NADS+5,5)=NADS+16                        COEFADS    67
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      A(NADS+6,1)=GELAP  $ ICOL(NADS+5,1)=NADS+5                        COEFADS   68
      A(NADS+6,2)=1.     $ ICOL(NADS+6,2)=NADS+6                        COEFADS   69
                                                                        COEFADS   70
      A(NADS+7,1)=-KA2YT  $ ICOL(NADS+7,1)=NADS+2                       COEFADS   71
      A(NADS+7,2)=-KA2AP  $ ICOL(NADS+7,2)=NADS+5                       COEFADS   72
      A(NADS+7,3)=1.      $ ICOL(NADS+7,3)=NADS+7                       COEFADS   73
                                                                        COEFADS   74
      A(NADS+8,1)=-GMLA2  $ ICOL(NADS+8,1)=NADS+7                       COEFADS   75
      A(NADS+8,2)=1.      $ ICOL(NADS+8,2)=NADS+8                       COEFADS   76
                                                                        COEFADS   77
      A(NADS+9,1)=-SZTA1  $ ICOL(NADS+9,1)=NADS+4                       COEFADS   78
      A(NADS+9,2)=-SZTA2  $ ICOL(NADS+9,2)=NADS+8                       COEFADS   79
      A(NADS+9,3)=1.      $ ICOL(NADS+9,3)=NADS+9                       COEFADS   80
      A(NADS+9,4)=-SZTP1  $ ICOL(NADS+9,4)=NADS+12                      COEFADS   81
      A(NADS+9,5)=-SZTP2  $ ICOL(NADS+9,5)=NADS+16                      COEFADS   82
                                                                        COEFADS   83
      A(NADS+10,1)=GEL7T  $ ICOL(NADS+10,1)=NADS+9                      COEFADS   84
      A(NADS+10,2)=1.     $ ICOL(NADS+10,2)=NADS+10                     COEFADS   85
                                                                        COEFADS   86
      A(NADS+11,1)=-KB17T  $ ICOL(NADS+11,1)=NADS+10                    COEFADS   87
      A(NADS+11,2)=1.      $ ICOL(NADS+11,2)=NADS+11                    COEFADS   88
      A(NADS+11,3)=-KB1FP  $ ICOL(NADS+11,3)=NADS+14                    COEFADS   89
                                                                        COEFADS   90
C     C     C     C     C     C     C     C     C                       COEFADS   91
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      A(NADS+12,1)=-GMLB1  $ ICOL(NADS+12,1)=NADS+11                    COEFADS    92
      A(NADS+12,2)=1.   $ ICOL(NADS+12,2)=NADS+12                       COEFADS    93
C                                                                       COEFADS    94
      A(NADS+13,1)=-SBPA1  $ ICOL(NADS+13,1)=NADS+4                     COEFADS    95
      A(NADS+13,2)=-SBPA2  $ ICOL(NADS+13,2)=NADS+8                     COEFADS    96
      A(NADS+13,3)=-SBPB1  $ ICOL(NADS+13,3)=NADS+12                    COEFADS    97
      A(NADS+13,4)=1.   $ ICOL(NADS+13,4)=NADS+13                       COEFADS    98
      A(NADS+13,5)=-SBPB2  $ ICOL(NADS+13,5)=NADS+16                    COEFADS    99
C                                                                       COEFADS   100
      A(NADS+14,1)=GELBP  $ ICOL(NADS+14,1)=NADS+13                     COEFADS   101
      A(NADS+14,2)=1.   $ ICOL(NADS+14,2)=NADS+14                       COEFADS   102
C                                                                       COEFADS   103
      A(NADS+15,1)=-KB2ZT  $ ICOL(NADS+15,1)=NADS+10                    COEFADS   104
      A(NADS+15,2)=-KB2BP  $ ICOL(NADS+15,2)=NADS+14                    COEFADS   105
      A(NADS+15,3)=1.   $ ICOL(NADS+15,3)=NADS+15                       COEFADS   106
C                                                                       COEFADS   107
      A(NADS+16,1)=-GMLB2  $ ICOL(NADS+15,1)=NADS+15                    COEFADS   108
      A(NADS+16,2)=1.   $ ICOL(NADS+16,2)=NADS+16                       COEFADS   109
C                                                                       COEFADS   110
C                                                                       COEFADS   111
      RETURN                                                            COEFADS   112
      END                                                               COEFADS   113
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      COMPLEX FUNCTION G(S,N,R)                                          FUNCTIONG    2
      COMPLEX GI,LPF,AAACMP,AAECMP,APAP,EPAP,AFBLP,EFBLP,                FUNCTIONG    3
     1 AEQVBP,EEQVBP,XINTNT,A,B,P,S                                      FUNCTIONG    4
      COMPLEX GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,            FIRST       10
     1 GFB2,GAB2,GMB2,GLB21,GLB22,GFLZT,GELBP,GMLB1,GMLB2,               FIRST       11
     2GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                              FIRST       12
     3  GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                            FIRST       13
     4    GELYT,GELAP,GMLA1,GMLA2,GRSHOD,GLOWPS                         COMPFIL2     4
      REAL KZT,KBP,KB1,KB2,KYT,KAP,KA1,KA2,KB1ZT,KB2ZT,                  FIRST       15
     1     KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP                          FIRST       16
      REAL P,EPSO,ETAO,EPSI,ETAI                                         FUNCTIONG    5
      DIMENSION R(80)                                                    FUNCTIONG    6
C                                                                        FUNCTIONG    7
      COMMON/ALL/P(150),NR,NW,ISTART,METHOD                              FUNCTIONG    8
      COMMON/AAIII/ETAO,EPSO,AK,BK,CA,CB,XKA,XKB,AZMOT,ELMOT,AJ,EJ,      FUNCTIONG    9
     1 AOPTG,EOPTG,XG1,XG2,LPF,AAACMP,AAECMP,APAP,EPAP,AFBLP,EFBLP,      FUNCTIONG   10
     2 XINTNT,EEQVBP,AEQVBP                                              FUNCTIONG   11
C                                                                        FUNCTIONG   12
CC                                                                       FUNCTIONG   13
      COMMON /CADAS/ SYTAA,SAPAA,AZTAA,SBPAA,SYTBA,SAPBA,SZTBA,SBPBA,    FIRST       17
     1               YT,AP,ZT,BP,KYT,KAP,KA1,KA2,KZT,KBP,KB1,KB2,        FIRST       18
     2               YTCW2,YTCW1,APCW2,APCW1,ZTCW2,ZTCW1,BPCW2,BPCW1,     FIRST       19
     3               YTSGAN,APSGAN,A1MFBO,A2MFBO,                        FIRST       20
     4               ZTSGAN,BPSGAN,B1MFBO,B2MFBO,                        FIRST       21
     5               A1LSF,A2LSF,B1LSF,B2LSF,                            FIRST       22
     7               WFYT,ZFYT,WFAP,ZFAP,WFA1,ZFA1,WFA2,ZFA2,            FIRST       23
     8               WLA11,ZLA11,WLA12,ZLA12,WLA21,ZLA21,WLA22,ZLA22,    FIRST       24
     9               WFZT,ZFZT,WFBP,ZFBP,WFB1,ZFB1,WFB2,ZFB2,            FIRST       25
     Z               WLB11,ZLB11,WLB12,ZLB12,WLB21,ZLB21,WLB22,ZLB22,    FIRST       26
     B               SYTA1,SYTA2,SYTB1,SYTB2,SAPA1,SAPA2,SAPB1,SAPB2,    FIRST       27
     C               SZTA1,SZTA2,SZTB1,SZTB2,SBPA1,SBPA2,SBPB1,SBPB2,    FIRST       28
     D               KB1ZT,KB2ZT,KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP,    FIRST       29
     E               SYTGA,SAPGA,SZTGA,SBPGA                             FIRST       30
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      COMMON /GADAS/ GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,      FIRST      31
     1               GFB2,GAB2,GMB2,GLB21,GLB22,GFLZT,GELBP,GMLB1,GMLB2,  FIRST      32
     2               GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                FIRST      33
     3               GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                FIRST      34
     4                GELYT,GELAP,GMLA1,GMLA2,GBSMOD,GLOWPS               COMPFIL2    5
C                                                                         FIRST      36
C                                                                         FIRST      37
      NADS=49                                                             FIRST      38
C                                                                         FIRST      39
      GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18) N              FIRST      40
C                                                                         FIRST      41
C                                                                         FIRST      42
C AP ERROR REJECTION                                                      FIRST      43
    1 G=R(5+NADS)                                                         FIRST      44
      RETURN                                                              FIRST      45
C                                                                         FIRST      46
C BP ERROR REJECTION                                                      FIRST      47
    2 G=R(13+NADS)                                                        FIRST      48
      RETURN                                                              FIRST      49
C                                                                         FIRST      50
C YT ERROR REJECTION                                                      FIRST      51
    3 G=R(1+NADS)                                                         FIRST      52
      RETURN                                                              FIRST      53
C                                                                         FIRST      54
C ZT ERROR REJECTION                                                      FIRST      55
    4 G=R(9+NADS)                                                         FIRST      56
      RETURN                                                              FIRST      57
C                                                                         FIRST      58
```

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C       BACK-IN TO A2 AMPLIFIER OUTPUT                                  FIRST      59
     5  G=R(NADS+8)/GBSMOD/GLA22/GLA21/A2LSF/GAA2*2.                    FIRST      60
        RETURN                                                          FIRST      61
C                                                                       FIRST      62
C       BACK-IN TO A1 AMPLIFIER OUTPUT                                  FIRST      63
     6  G=R(NADS+4)/GBSMOD/GLA12/GLA11/A1LSF/GAA1*2.                    FIRST      64
        RETURN                                                          FIRST      65
C                                                                       FIRST      66
C       BACK-IN TO B2 AMPLIFIER                                         FIRST      67
     7  G=R(NADS+16)/GBSMOD/GLB22/GLB21/B2LSF/GAB2*2.                   FIRST      68
        RETURN                                                          FIRST      69
C                                                                       FIRST      70
C       BACK-IN TO B1 AMPLIFIER                                         FIRST      71
     8  G=R(NADS+12)/GBSMOD/GLB12/GLB11/B1LSF/GAB1*2.                   FIRST      72
        RETURN                                                          FIRST      73
C                                                                       FIRST      74
C       TORQUE OUTPUT FROM A1 MOTOR  (NODE 17)                          FIRST      75
      9 G=R(NADS+4)/GBSMOD/GLA12/GLA11/A1LSF                            FIRST      76
        RETURN                                                          FIRST      77
C                                                                       FIRST      78
C       TORQUE OUTPUT FROM A2 MOTOR  (NODE 18)                          FIRST      79
     10 G=R(NADS+8)/GBSMOD/GLA22/GLA21/A2LSF                            FIRST      80
        RETURN                                                          FIRST      81
C                                                                       FIRST      82
C       TORQUE OUTPUT FROM B1 MOTOR  (NODE 19)                          FIRST      83
     11 G=R(NADS+12)/GBSMOD/GLB12/GLB11/B1LSF                           FIRST      84
        RETURN                                                          FIRST      85
C                                                                       FIRST      86
C       TORQUE OUTPUT FROM B2 MOTOR  (NODE 20)                          FIRST      87
     12 G=R(NADS+16)/GBSMOD/GLB22/GLB21/B2LSF                           FIRST      88
        RETURN                                                          FIRST      89
C                                                                       FIRST      90
```

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C              Y- TRANS OPEN LOOP RESPONSE    TRUE                    PROVEIT      1
 13    G=(R(NADS+4)*SYTA1+R(NADS+8)*SYTA2)/R(NADS+1)                    PROVEIT      2
       RETURN                                                          FIRST       93
C                                                                      FIRST       94
C              ALPHA-P OPEN LOOP RESPONSE    TRUE                     PROVEIT      3
 14    G=(R(NADS+8)*SAPA2)+(R(NADS+4)*SYTA1)/(R(NADS+5))                PROVEIT      4
       RETURN                                                          FIRST       97
C                                                                      FIRST       98
C      BETA-P OPEN LOOP RESPONSE                                       FIRST       99
 15    P=R(NADS+16)*SBPP2/R(NADS+13)                                   FIRST      100
       RETURN                                                          FIRST      101
C                                                                      FIRST      102
C      Z-TRANS OPEN LOOP RESPONSE                                      FIRST      103
 16    G=R(NADS+12)*SZTB1/R(NADS+9)                                    FIRST      104
       RETURN                                                          FIRST      105
C                                                                      FIRST      106
C      A1 MIRROR DEFLECTION                                            FIRST      107
 17    G=R(NADS+4)                                                     FIRST      108
       RETURN                                                          FIRST      109
C                                                                      FIRST      110
C      A2 MIRROR DEFLECTION                                            FIRST      111
 18    G=R(NADS+8)                                                     FIRST      112
       RETURN                                                          FIRST      113
C                                                                      FIRST      114
       END                                                             FIRST      115
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      SUBROUTINE COEF(A,B,ICOL,NEQN,NROW,NCOL,S,N,R)                    COEF     2
C                                                                       COEF     3
CC                                                                      COEF     4
C     THIS ROUTINE COMBINES APT AND AA MODELS                           COEF     5
CC                                                                      COEF     6
C                                                                       COEF     7
      COMPLEX A(NROW,NCOL),B(NROW),R(NROW),S                            COEF     8
C                                                                       COEF     9
      INTEGER ICOL(NROW,NCOL)                                           COEF    10
C                                                                       COEF    11
      REAL KYT,KAP,KA1,KA2,KZT,KBP,KB1,KB2,KB1ZT,KB2ZT,KB1BP,          COEF    12
     1     KB2BP,KA1YT,KA2YT,KA1AP,KA2AP                                COEF    13
C                                                                       COEF    14
      COMPLEX GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,           COEF    15
     1     GFB2,GAB2,GMB2,GLB21,GLB22,GFLZT,GFLBP,GMLB1,GMLB2,          COEF    16
     2      GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                       COEF    17
     3      GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                       COEF    18
     4    GFLYT,GFLAP,GMLA1,GMLA2,GBSWP,GLOWPS                         COMPFIL2 2
      REAL ETAO,EPSO,AASANG,MTEL,TWOPI                                  COEF    20
C                                                                       COEF    21
      REAL P,JAZI,JAZO,KAZI,KAZO,                                       COEF    22
     $       JELI,JELO,KELI,KELO,KPI                                    COEF    23
C                                                                       COEF    24
      COMPLEX                                                           COEF    25
     $ C2,C3,C4,C5,C7,C8,C9,C10,C11,C13,C15,C16,C17,C18,C20,            COEF    26
     $ C1AZ,C8AZ,C12AZ,C14AZ,                                           COEF    27
     $ C1EL,C8EL,C12EL,C14EL,                                           COEF    28
     $ V1,V2,V3,V4,GI,                                                  COEF    29
     $ G1,G2,G3,G6,G7,G8,G9,                                            COEF    30
     $ F1,F2,F3,F4,F5,F6                                                COEF    31
C                                                                       COEF    32
      COMMON/DSTURB/                                                    COEF    33
     $ AIDOT,AOKDOT,AOJDOT,AOEDOT,RPHIDT,RPSIDT,RTHEDT                  COEF    34
     $ ,AIEDOT,AWJA,AWJB                                                COEF    35
C                                                                       COEF    36
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      COMMON/APTCS/                                                          COEF       37
     $ C2,C3,C4,C5,C7,C8,C9,C10,C11,C13,C15,C16,C17,C18,C20,                 COEF       38
     $ C1AZ,C6AZ,C12AZ,C14AZ,                                               COEF       39
     $ C1EL,C6EL,C12EL,C14EL,                                               COEF       40
     $ V1,V2,V3,V4,GI,                                                      COEF       41
     $ G1,G2,G3,G6,G7,G8,G9,                                                COEF       42
     $ F1,F2,F3,F4,F5,F6                                                    COEF       43
C                                                                           COEF       44
      COMMON /CADAS/ SYTAA,SAPAA,SZTAA,SBPAA,SYTBA,SAPBA,SZTBA,SBPBA,       COEF       45
     1               YT,AP,ZT,BP,KYT,KAP,KA1,KA2,KZT,KBP,KB1,KB2,           COEF       46
     2               YTCW2,YTCW1,APCW2,APCW1,ZTCW2,ZTCW1,BPCW2,BPCW1,        COEF       47
     3               YTSGAN,APSGAN,A1MERO,A2MERO,                           COEF       48
     4               ZTSGAN,BPSGAN,B1MERO,B2MERO,                           COEF       49
     5               A1LSF,A2LSF,B1LSF,B2LSF,                               COEF       50
     7               WFYT,ZFYT,WFAP,ZFAP,WFA1,ZFA1,WFA2,ZFA2,               COEF       51
     8               WLA11,ZLA11,WLA12,ZLA12,WLA21,ZLA21,WLA22,ZLA22,       COEF       52
     9               WFZT,ZFZT,WFBP,ZFBP,WFB1,ZFB1,WFB2,ZFB2,               COEF       53
     A               WLB11,ZLB11,WLB12,ZLB12,WLB21,ZLB21,WLB22,ZLB22,       COEF       54
     B               SYTA1,SYTA2,SYTB1,SYTB2,SAPA1,SAPA2,SAPB1,SAPB2,       COEF       55
     C               SZTA1,SZTA2,SZTB1,SZTB2,SBPA1,SBPA2,SBPB1,SBPB2,       COEF       56
     D               KB1ZT,KB2ZT,KB1BP,KB2BP,KA1YT,KA2YT,KA1AP,KA2AP,       COEF       57
     E               SYTGA,SAPGA,SZTGA,SBPGA                                COEF       58
      COMMON /GADAS/ GFZT,GCZT,GFB1,GAB1,GMB1,GLB11,GLB12,GFBP,GCBP,        COEF       59
     1               GFB2,GAB2,GMB2,GLB21,GLB22,GELZT,GELBP,GMLB1,GMLB2,    COEF       60
     2               GFYT,GCYT,GFA1,GAA1,GMA1,GLA11,GLA12,                  COEF       61
     3               GFAP,GCAP,GFA2,GAA2,GMA2,GLA21,GLA22,                  COEF       62
     4               GELYT,GELAP,GMLA1,GMLA2,GBSMOD,GLOWPS                  COMPFIL2    3
C                                                                           COEF       64
C                                                                           COEF       65
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      COMMON/ALL/P(150),NR,NN,ISTART,METHOD                                  COEF      65
      EQUIVALENCE                                                            COEF      66
C                                                                            COEF      67
C          AZIMUTH                ELEVATION                 BOTH           COEF      68
C                                                                            COEF      69
     $ ( P(11), JAZI   ),    ( P(21), JELI   ),    ( P( 1), ETAI   ),       COEF      70
     $ ( P(12), JAZO   ),    ( P(22), JELO   ),    ( P( 2), ETAO   ),       COEF      71
     $ ( P(13), DMAZI  ),    ( P(23), DMELI  ),    ( P( 3), EPSI   ),       COEF      72
     $ ( P(14), DMAZO  ),    ( P(24), DMELO  ),    ( P( 4), EPSO   ),       COEF      73
     $ ( P(15), AZSLGN),     ( P(25), ELSLGN),     ( P( 5), BETA   ),       COEF      74
     $ ( P(16), AZSTGN),     ( P(26), ELSTGN),     ( P( 6), ZETA   ),       COEF      75
     $ ( P(17), AZOSTB),     ( P(27), ELOSTB),     ( P( 7), WTIINV),        COEF      76
     $ ( P(18), A6     ),    ( P(28), E6     ),    ( P( 8), KPI    ),       COEF      77
     $ ( P(19), KAZI   ),    ( P(29), KELI   ),    ( P( 9), PVI1   ),       COEF      78
     $ ( P(20), KAZO   ),    ( P(30), KELO   ),    ( P(10), PVO2   ),       COEF      79
C                                                                            COEF      80
     $ ( P(31), AZIKGN),     ( P(41), ELIKGN),     ( P(51), WVAL   ),       COEF      81
     $ ( P(32), AZEFGN),     ( P(42), ELEFGN),     ( P(52), ZVI1   ),       COEF      82
     $ ( P(33), AZPVO1),     ( P(43), ELPVO1),     ( P(53), PVI2   ),       COEF      83
     $ ( P(34), AZKLI  ),    ( P(44), ELKLI  ),    ( P(54), ZVO2   ),       COEF      84
     $ ( P(35), AZKPO  ),    ( P(45), ELKPO  ),    ( P(55), TAU    ),       COEF      85
     $ ( P(36), AZVOLI),     ( P(46), ELVOLI),                              COEF      86
     $ ( P(37), AZVOLO),     ( P(47), ELVOLO),                              COEF      87
     $ ( P(38), ZVO1AZ),     ( P(48), ZVO1EL),                              COEF      88
     $ ( P(39), AZKLO  ),    ( P(49), ELKLO  )                              COEF      89
C                                                                            COEF      90
      EQUIVALENCE                                                            COEF      91
     $ ( P(61), DAZI   ),    ( P(62), DELI   )                              COEF      92
     $ ( P(63), DAZO   ),    ( P(64), DELO   )                              COEF      93
C                                                                            COEF      94
C     SET ROLL,YAW,PITCH INPUTS                                              COEF      95
C     ROLL                                                                   COEF      96
      RRHDT = P(125)                                                         COEF      97
C     YAW                                                                    COEF      98
      RPSIDT = P(126)                                                        COEF      99
C     PITCH                                                                  COEF     100
      RTHEDT = P(127)                                                        COEF     101
C     THE APT WILL BE PLACED FIRST INTO MATRIX A                             COEF     102
```

```
C                                                                       COEF      103
      IAPT = 0                                                          COEF      104
      JAPT = 0                                                          COEF      105
      CALL CCEFAPT(A,B,ICOL,NEQN,NROW,NCOL,S,N,R,IAPT,JAPT)             COEF      106
C                                                                       COEF      107
C                                                                       COEF      108
C     NEXT PLACE AA INTO MATRIX A, AA WILL START AT A(34,34)            COEF      109
C                                                                       COEF      110
      NAAS = 33                                                         COEF      111
      CALL CCEFAAS(A,B,ICOL,NEQN,NROW,NCOL,S,N,R,NAAS)                  COEF      112
C                                                                       COEF      113
C      SET COMMON TERMS BETWEEN APT AND AAS                             COEF      114
C                                                                       COEF      115
      A(NAAS+15,3)=2./S   SICOL(NAAS+15,3)=20+JAPT                      COEF      116
      A(NAAS+7,3)=2./S   SICOL(NAAS+7 ,3)=5+JAPT                        COEF      117
      A(NAAS+6,3)=COS(EPSO)    SICOL(NAAS+6,3)=10+JAPT                  COEF      118
      A(NAAS+14,3)=1.     SICOL(NAAS+14,3)=25+JAPT                      COEF      119
C                                                                       COEF      120
C                                                                       COEF      121
C     NEXT PLACE ADAS INTO MARTIX A, ADAS WILL START AT A(50,50)        COEF      122
C                                                                       COEF      123
      NADS = 49                                                         COEF      124
      ISOL=B(100)+NADS                                                  FIRST       1
      B(ISOL)=(1.0,0.0)                                                 FIRST       2
      KKK=ISOL-1                                                        FIRST       3
      DO 175 I=1,KKK                                                    FIRST       4
  175 B(I)=(0.0,0.0)                                                    FIRST       5
      KKK=ISOL+1                                                        FIRST       6
      DO 176 I=KKK,NROW                                                 FIRST       7
  176 B(I)=(0.0,0.0)                                                    FIRST       8
      CALL CCEFADS(A,B,ICOL,NEQN,NROW,NCOL,S,N,R,NADS)                  FIRST       9
      GO TO 99                                                          COEF      127
C                                                                       COEF      128
C     THERE ARE NO COUPLING TERMS BETSEEN ADAS AND APT                  COEF      129
C       OR ADAS AND AA AT PRESENT CODING                                COEF      130
C                                                                       COEF      131
```

```
C ********************************************************************** COEE  132
C                                                                        COEE  133
C      THIS SECTION SUPPLIES DISTURBANCE INPUTS TO ALL SUBSYSTEMS        COEE  134
C                                                                        COEE  135
C                                                                        COEE  136
C      INPUTS OF PITCH, ROLL, AND YAW ARE ENTERED AS RATES WITH          COEE  137
C              FOLLOWING ACRONYMS-                                       COEE  138
C                  PITCH RATE = RTHEDT                                   COEE  139
C                  ROLL RATE = RPHIDT                                    COEE  140
C                  YAW RATE = RPSIDT                                     COEE  141
C                                                                        COEE  142
C**********************************************************************  COEE  143
C                                                                        COEE  144
C      FIRST CODE BASE INPUTS TO APT                                     COEE  145
C                                                                        COEE  146
C     ACCELERATION DISTURBANCE TO INNER LOOPS                            COEE  147
C                                                                        COEE  148
      B(IAPT+5) = GI*AICDT                                               COEE  149
      B(IAPT+20) = GI*AIEDDT                                             COEE  150
C                                                                        COEE  151
C      ACCELERATION AND ANGULAR RATE DISTURBANCE INPUTS TO OUTER LOOPS   COEE  152
C                                                                        COEE  153
      B(IAPT+10) = -GI*ACKDDT+GI*C13*RPSIDT                              COEE  154
      B(IAPT+11) = -GI*RPSIDT                                            COEE  155
      B(IAPT+25) = GI*C20*COS(ETAO)*RTHEDT                               COEE  156
     1 -GI*C20*SIN(ETAO)*RPHIDT + GI*ADJDDT                              COEE  157
      B(IAPT+26) = GI*COS(ETAO)*RTHEDT-GI*SIN(ETAO)*RPHIDT               COEE  158
C                                                                        COEE  159
C      DISTURBANCE ALONG LOS                                             COEE  160
C                                                                        COEE  161
      B(IAPT+32) = SIN(ETAO)*RTHEDT+COS(ETAO)*RPHIDT                     COEE  162
C                                                                        COEE  163
C     END OF APT EXCITATION                                              COEE  164
C                                                                        COEE  165
```

```
C*********************************************************************** COEF      166
C                                                                       COEF      167
C     NEXT ARE INPUTS TO AA SUBSYSTEM                                   COEF      168
C                                                                       COEF      169
C                                                                       COEF      170
C     BASE MOTION INTO AA SENSORS                                       COEF      171
C                                                                       COEF      172
C                                                                       COEF      173
C*********************************************************************** COEF      174
C                                                                       COEF      175
C     NEXT CODE INPUTS TO ADAS SYSTEM                                   COEF      176
C                                                                       COEF      177
C                                                                       COEF      178
C      SENSITIVETY COEFFICIENTS ARE DEFINED IN BLOCK DATA FOR ADAS AND  COEF      179
C      COMMUNICATED THROUGH ADSCOM.                                     COEF      180
C                                                                       COEF      181
C     DEFINE BENCH RESPONSE TO BASE MOTION                              COEF      182
C                                                                       COEF      183
      TWOPI = 6.2831853                                                 COEF      184
      WNP = 20.*TWOPI                                                   COEF      185
      WNR = WNP                                                         COEF      186
      WNY = 25.*TWOPI                                                   COEF      187
      ZETANP = 0.05                                                     COEF      188
      ZETANR = 0.05                                                     COEF      189
      ZETANY = 0.05                                                     COEF      190
      BISOLP = (WNP*WNP+2.*ZETANP*WNP*S)/(S*S+2.*WNP*ZETANP*S+WNP*WNP)  COEF      191
      BISOLR = BISOLP                                                   COEF      192
      BISOLY =(WNY*WNY+2.*ZETANY*WNY*S)/(S*S+2.*WNY*ZETANY*S+WNY*WNY)   COEF      193
C                                                                       COEF      194
C     WRITE EQUATIONS FOR MOTION SEEN BY SENSORS                        COEF      195
C     Y TRANSLATION                                                     COEF      196
      B(1+NADS) = SYTAA*GI*(1.-BISOLP)*RTHEDT-SYTBA*GI*(1.-BISOLR)      COEF      197
     1 *RPHIDT-SYTGA*GI*(1.-BISOLY)*RPSIDT                              COEF      198
C                                                                       COEF      199
```

```
C      ALPHA ANGLE                                                          COEF      200
       R(5+NADS)= SAPAA*GI*(1.-RISOLR)*RTHEDT                               COEF      201
      1  -SAPBA*GI*(1.-RISOLR)*RPHIDT - ANJA                                COEF      202
C                                                                           COEF      203
C      Z TRANSLATION                                                        COEF      204
       R(10+NADS) = SZTGA*GI*(1.-RISOLY)*RPSIDT                             COEF      205
      1       -SZTBA*GI*(1.-RISOLR)*RPHIDT                                 COEF      206
      2      -SZTAA*GI*(1.-RISOLR)*RTHEDT                                  COEF      207
C                                                                           COEF      208
C      BETA ANGLE                                                           COEF      209
       R(13+NADS) = SBPBA*GI*(1.-RISOLR)*RPHIDT                             COEF      210
      1      -SBPAA*GI*(1.-RISOLR)*RTHEDT - ANJB                           COEF      211
C                                                                           COEF      212
C      NO TRANSLATION DISTURBANCES CODED AT PRESENT TIME SINCE NO DATA AV    COEF      213
C                                                                           COEF      214
C**********                                              ************       COEF      215
C**********      END OF BASE FORCING FUNCTION            **************     COEF      216
C**********                                              **************     COEF      217
C*****************************************************************************COEF      218
C*****************************************************************************COEF      219
C                                                                           COEF      220
C      THE FOLLOWING SECTION IS COMBINED OPTICAL JITTER FROM                COEF      221
C        COMBINATION OF SUBSYSTEMS                                          COEF      222
C*****************************************************************************COEF      223
C                                                                           COEF      224
C                                                                           COEF      225
   99 CONTINUE                                                              COEF      226
       MTEL = 6                                                             COEF      227
       NOPT = 65                                                            COEF      228
C      APT CONTRIBUTION                                                     COEF      229
C      R(1+NOPT) IS AZ BEAM JITTER                                          COEF      230
C      R(2+NOPT) IS EL BEAM JITTER                                          COEF      231
C                                                                           COEF      232
```

AD-A056 093 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO SCH--ETC F/G 20/6
ANALYSIS AND DESIGN MODIFICATION OF AN AIRBORNE MIRROR ALIGNMEN--ETC(U)
MAR 78 P D NUTZ

UNCLASSIFIED AFIT/GAE/AA/78M-12 NL

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```
      A(NOPT+1,1) = (1./MTEL)*SIN(EPSO-ETAO)      $ICOL(NOPT+1,1) =5+NAOS COEF      233
      A(NOPT+1,2)=(1./MTEL)*COS(EPSO-ETAO)       $ICOL(NOPT+1,2)=13+NAOS  COEF      234
      A(NOPT+1,3)=-(1./MTEL)    $ICOL(NOPT+1,3)=1+NAAS                    COEF      235
      A(NOPT+1,4)=-(MTEL-1.)/MTEL*GI               $ICOL(NOPT+1,4)=5+IAPT  COEF      236
      A(NOPT+2,1)=-(1./MTEL)*SIN(EPSO-ETAO)        $ICOL(NOPT+2,1)=13+NAOS COEF      237
      A(NOPT+2,2)=(1./MTEL)*COS(EPSO-ETAO)         $ICOL(NOPT+2,2)=5+NAOS  COEF      238
      A(NOPT+2,3)=-(1./MTEL)                       $ICOL(NOPT+2,3)=9+NAAS  COEF      239
      A(NOPT+2,4) = -(MTEL-1.)/MTEL*GI             $ICOL(NOPT+2,4)=25+IAPT COEF      240
C                                                                           COEF      241
C     DEFINE FIVE EXTRA EQUATIONS FOR SPARES                                COEF      242
C                                                                           COEF      243
      A(NOPT+1,5)=1.        $ICOL(NOPT+1,5)=NOPT+1                        COEF      244
      A(NOPT+2,5)=1.          $ICOL(NOPT+2,5)=NOPT+2                      COEF      245
      A(NOPT+3,1) =  1.                $ICOL(NOPT+3,1) = NOPT+3           COEF      246
      A(NOPT+3,2) = -1.                $ICOL(NOPT+3,2) = NOPT + 1         COEF      247
      A(NOPT+4,1) = 1.                 $ICOL(NOPT+4,1) = NOPT + 4         COEF      248
      A(NOPT+4,2) = -1.                $ICOL(NOPT+4,2) = NOPT + 3         COEF      249
      A(NOPT+5,1) = 1.                 $ICOL(NOPT+5,1) = NOPT + 5         COEF      250
      A(NOPT + 5,2) = -1.              $ICOL(NOPT+5,2) = NOPT + 4         COEF      251
      A(NOPT+6,1) = 1.                 $ICOL(NOPT+6,1) = NOPT + 6         COEF      252
      A(NOPT+6,2) = -1.                $ICOL(NOPT+6,2) = NOPT + 5         COEF      253
      A(NOPT + 7,1) = 1.               $ICOL(NOPT+7,1) = NOPT + 7         COEF      254
      A(NOPT+7,2) = -1.                $ICOL(NOPT+7,2) = NOPT + 6         COEF      255
      A(NOPT+8,1) = 1.                 $ICOL(NOPT+8,1) = NOPT + 8         COEF      256
      A(NOPT+8,2) = -1.                $ICOL(NOPT+8,2) = NOPT + 7         COEF      257
C                                                                           COEF      258
C     USE ABOVE EQUATIONS WITHOUT CHANGES TO CALLING ROUTINES               COEF      259
C                                                                           COEF      260
                                                                            COEF      261
      RETURN                                                                COEF      262
      END                                                                   COEF      263
```

Appendix B

Diagrams of Two for One Beam Steering Movement

The understanding of the two for one mirror movement is crucial in understanding the ADAS control system. The need for the 2:1 ratio is discussed in the main section of this report and again in Ref. 1. This appendix attempts to explain the need through the use of several diagrams. These diagrams are not of the actual layout of the beam steering mirrors but the principle still applies.

Fig. 19 shows the initial position of each mirror, the sensor location, and the nominal position of the optical beam on target. The beam is completely aligned along its nominal path. In Fig. 20 , the beam has a pure translational misalignment X at the sensor face. In order to move the beam to strike the center of the target both mirrors must be moved counterclockwise exactly the same amount. Mirror #1 must always move to such an angle that the beam strikes the hinge (pivot) point of Mirror #2. This hinge point is called the "critical hinge point." Fig. 21 depicts the beam with pure angular misalignment at the sensor face. To correct for this pure angular disturbance Mirror #1 must move twice as far as Mirror #2. In a continuous system, Mirror #1 would also be required to move twice as fast as Mirror #2.

It is possible to have both angular and translational misalignment of the beam. This condition is shown in Fig. 22 . For the combination of errors, the mirror movement ratio (1:2) will be somewhere between 2:1 and 1:1. The actual ratio will depend on the relative magnitude of each error involved. In Fig. 22 , the ratio is 1.8:1.

This principle of beam steering movement may be directly applied to the ADAS beam steering mirrors. The only difference between these figures and the physical beam steering mirrors is that the errors may also occur due to movement of the target.

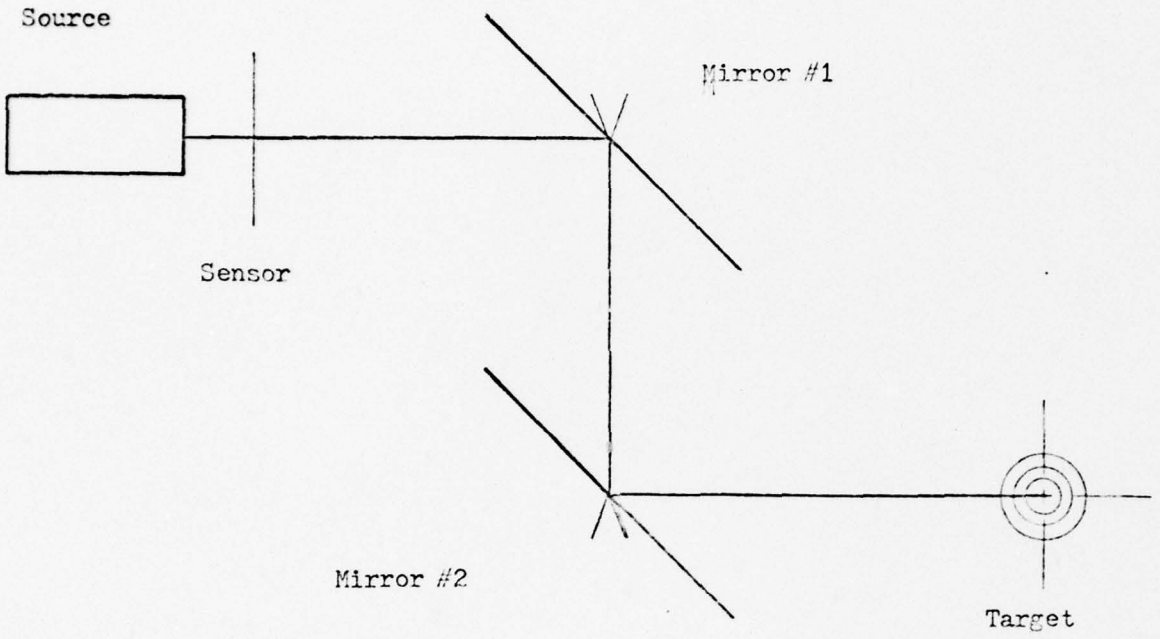


Fig. 19. Initial Position of Beam Steering Mirrors

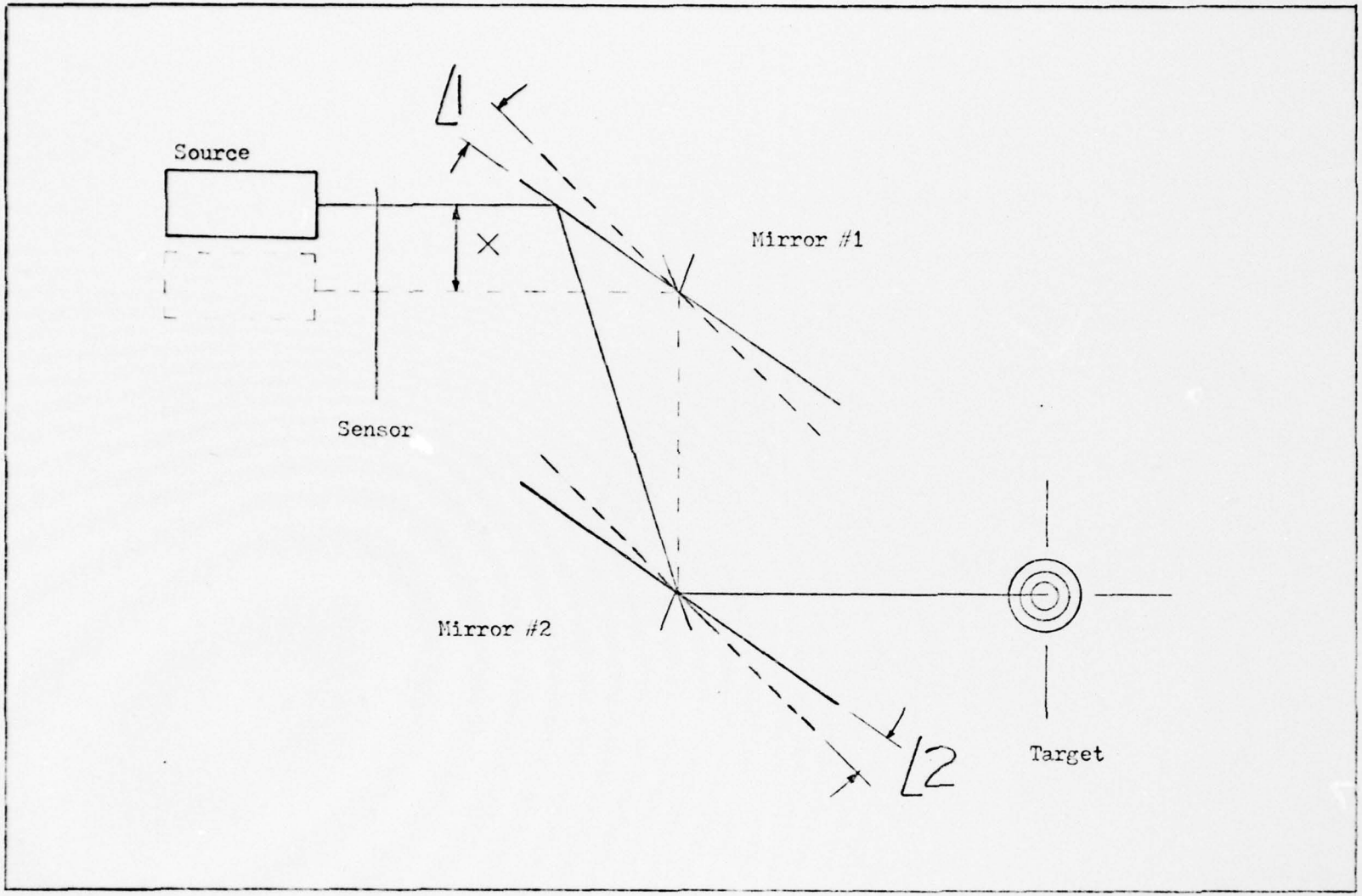


Fig.20. Pure Translational Error in Beam Alignment

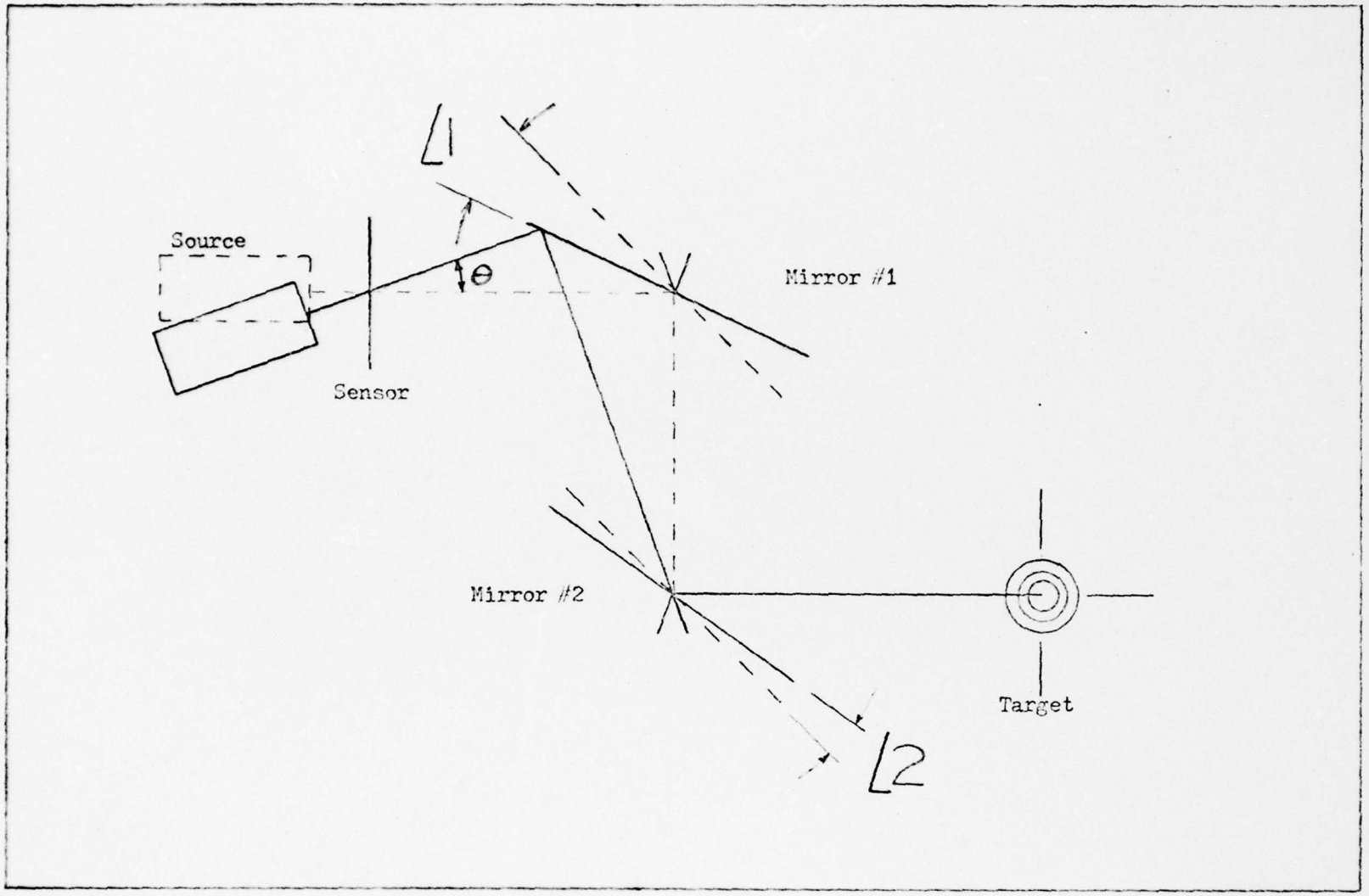


Fig.21. Pure Angular Error in Beam Alignment

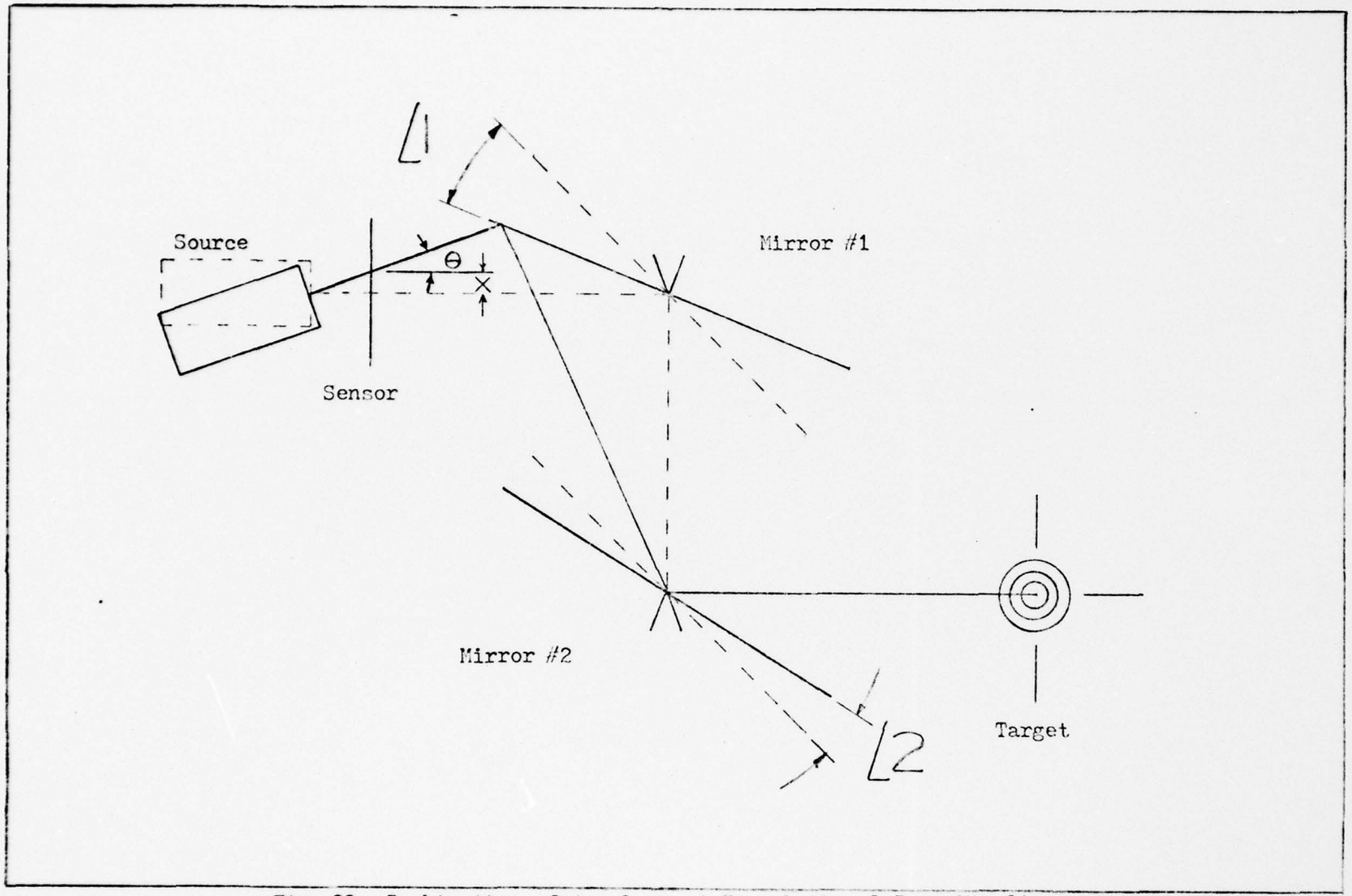


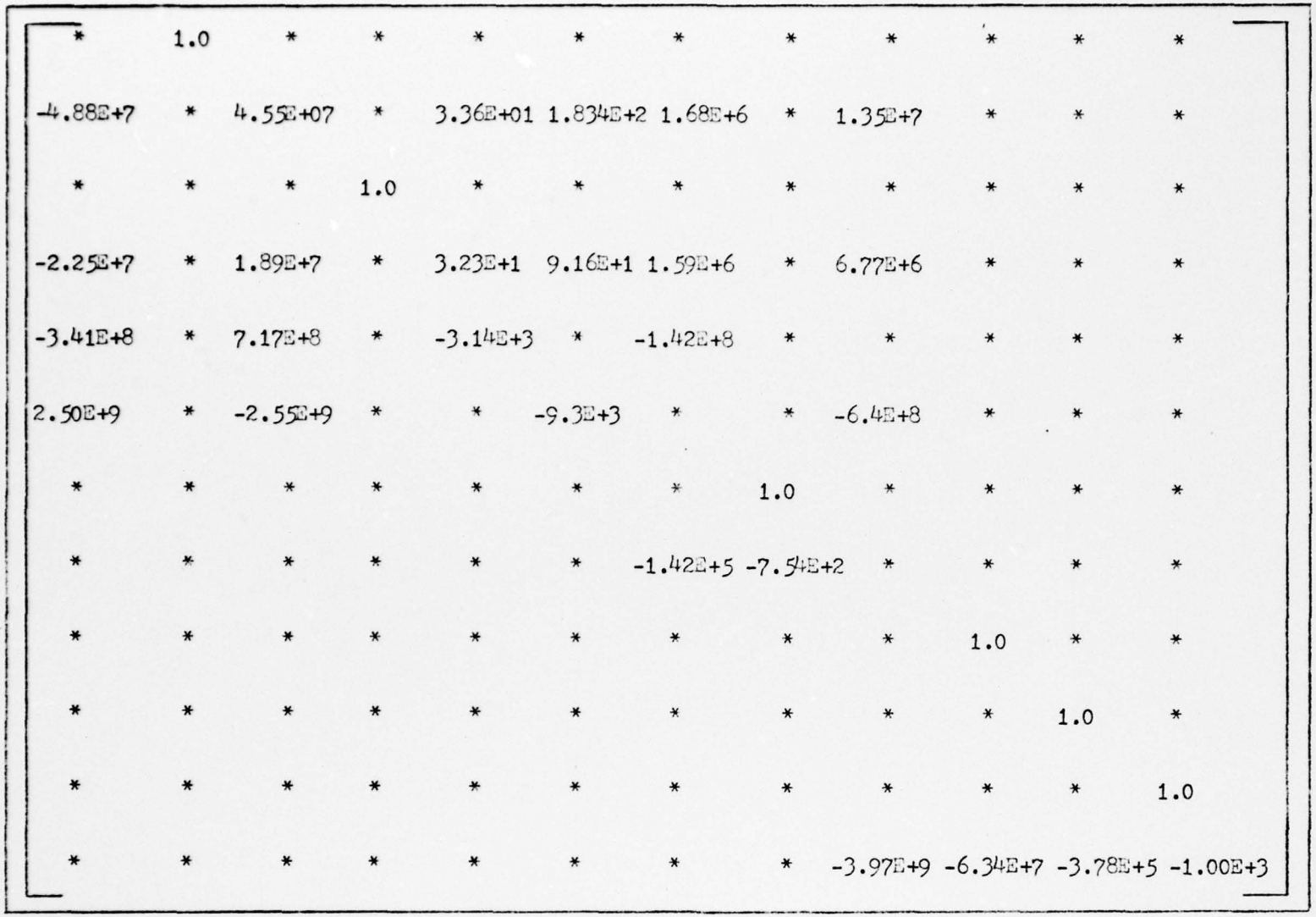
Fig. 22. Combination of Angular and Translational Beam Misalignment

Appendix C

Supplimentary Figures and Tables

```
      PROGRAM EIGEN(INPUT,OUTPUT)
      DIMENSION A(13,13),WORK(26)
      COMPLEX EIGVAL(13),EIGVEC(13,13)
      DATA(A(1,I),I=1,13)/0,1.0,11*0/
      DATA(A(2,I),I=1,13)/4.03E+6,0,-8.5E+6,0,33.5,
     10,1.68E+6,0,0,0,0,0,12.0/
      DATA(A(3,I),I=1,13)/0,0,0,1.0,9*0/
      DATA(A(4,I),I=1,13)/-2.25E+7,0,1.89E+7,0,3.23E+1,
     19.16E+1,1.59E+6,0,6.77E+6,4*0/
      DATA(A(5,I),I=1,13)/-3.41E+8,0,7.17E+8,0,
     1-3.14E+3,0,-1.42E+8,6*0/
      DATA(A(6,I),I=1,13)/2.50E+9,0,-2.56E+9,0,0,-9.3E+3,
     10,0,-6.4E+8,4*0/
      DATA(A(7,I),I=1,13)/0,0,0,0,0,0,0,1.0,5*0/
      DATA(A(8,I),I=1,13)/0,0,0,0,0,0,
     1-1.42E+5,-7.54E+2,5*0/
      DATA(A(9,I),I=1,13)/0,0,0,0,0,0,0,0,0,1.0,3*0/
      DATA(A(10,I),I=1,13)/0,0,0,0,0,0,0,0,0,0,1.0,0,0/
      DATA(A(11,I),I=1,13)/0,0,0,0,0,0,0,0,0,0,0,1.0,0/
      DATA(A(12,I),I=1,13)/0,0,0,0,0,0,0,0,
     1-3.97E+9,-6.34E+7,-3.78E+5,-1.0E+3,0/
      PRINT*,"ENTER ROW 13 OF MATRIX A"
      READ*,(A(13,I),I=1,13)
      PRINT 50,((A(I,J),J=1,13),I=1,13)
50    FORMAT(4E15.6)
      IND=1
      CALL RGEIG(13,13,A,IND,EIGVAL,EIGVEC,WORK)
      PRINT 100,IND
100   FORMAT("   ERROR = "I5/)
      DO 10 I=1,13
      PRINT 200, EIGVAL(I)
      PRINT 300,(EIGVEC(J,I),J=1,13)
10    CONTINUE
      CALL EXIT
200   FORMAT(///"  EIGENVALUE = "2F13.3/"  EIGENVECTOR =")
300   FORMAT(14X,2F13.3)
      STOP
      END
```

Fig.23 . ADAS State Space Model Computer Program



*	1.0	*	*	*	*	*	*	*	*	*	*
-4.88E+7	*	4.55E+07	*	3.36E+01	1.834E+2	1.68E+6	*	1.35E+7	*	*	*
*	*	*	1.0	*	*	*	*	*	*	*	*
-2.25E+7	*	1.89E+7	*	3.23E+1	9.16E+1	1.59E+6	*	6.77E+6	*	*	*
-3.41E+8	*	7.17E+8	*	-3.14E+3	*	-1.42E+8	*	*	*	*	*
2.50E+9	*	-2.55E+9	*	*	-9.3E+3	*	*	-6.4E+8	*	*	*
*	*	*	*	*	*	*	1.0	*	*	*	*
*	*	*	*	*	*	-1.42E+5	-7.54E+2	*	*	*	*
*	*	*	*	*	*	*	*	*	1.0	*	*
*	*	*	*	*	*	*	*	*	*	1.0	*
*	*	*	*	*	*	*	*	*	*	*	1.0
*	*	*	*	*	*	*	*	-3.97E+9	-6.34E+7	-3.78E+5	-1.00E+3

* = 0

Fig. 24 . State Matrix [A] for ADAS Two Loop Control System

*	1.0	*	*	*	*	*	*	*	*	*	*	*
4.03+6	*	-8.51+6	*	33.6+0	*	1.68+6	*	*	*	*	*	12.0
*	*	*	1.0	*	*	*	*	*	*	*	*	*
-2.3+7	*	1.97+7	*	3.2+1	9.2+1	1.6+6	*	6.8+6	*	*	*	*
-3.4+8	*	7.2+8	*	-3.1+3	*	-1.4+8	*	*	*	*	*	*
2.5+9	*	-2.6+9	*	*	-9.3+3	*	*	-6.4+8	*	*	*	*
*	*	*	*	*	*	*	1.0	*	*	*	*	*
*	*	*	*	*	*	-1.4+5	-7.5+2	*	*	*	*	*
*	*	*	*	*	*	*	*	*	1.0	*	*	*
*	*	*	*	*	*	*	*	*	*	1.0	*	*
*	*	*	*	*	*	*	*	*	*	*	1.0	*
*	*	*	*	*	*	*	*	-4+10	-6.3+7	-3.8+5	-1.0+3	*
-3.1+9	*	3.2+9	*	*	1.1+4	*	*	7.9+8	*	*	*	-7.0+2

* = 0

Fig. 25. State Space Matrix [A] for Modified ADAS Two Loop Control System

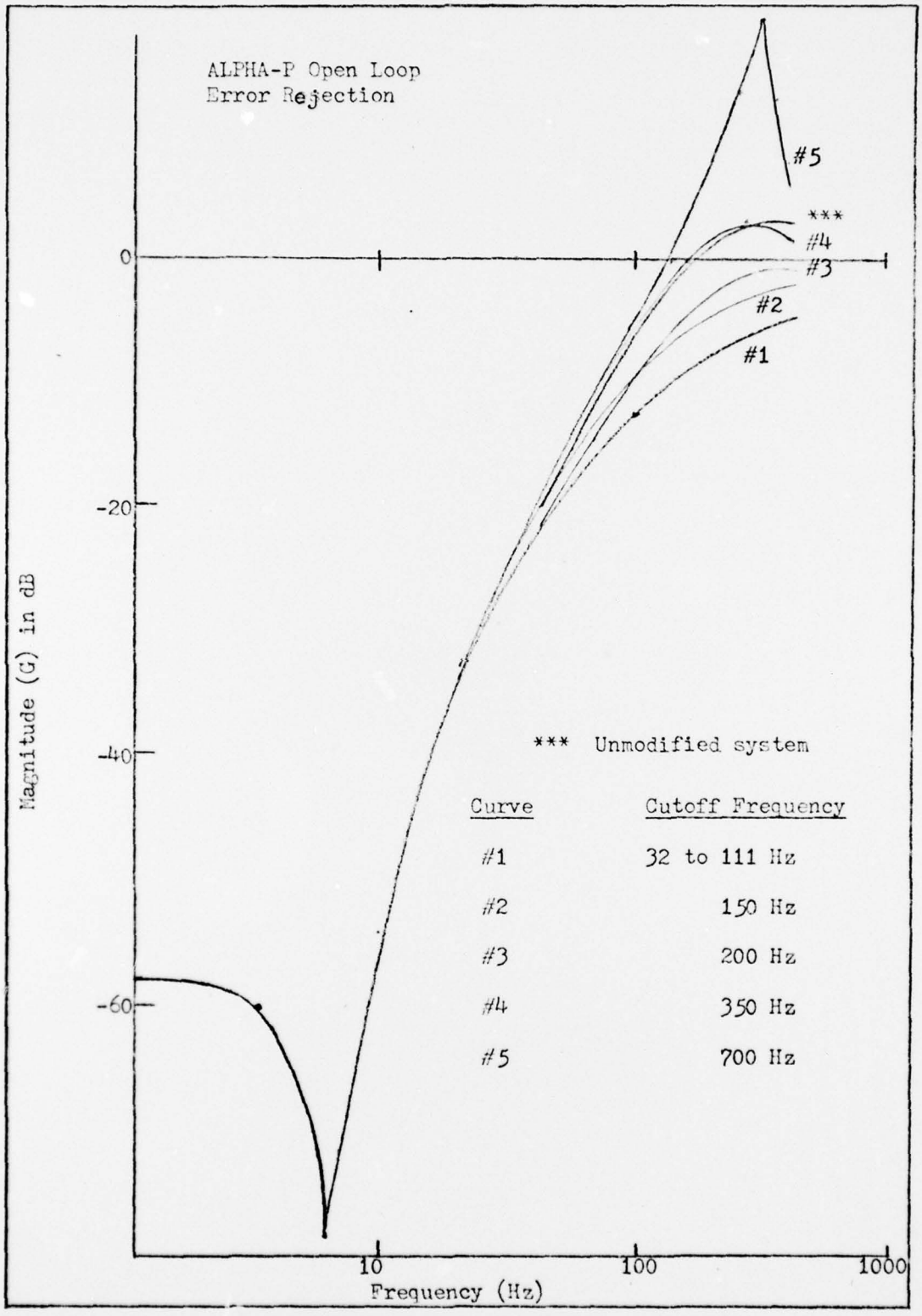


Fig.26. ALPHA-P Open Loop Error Rejection with Various Cutoff Frequencies

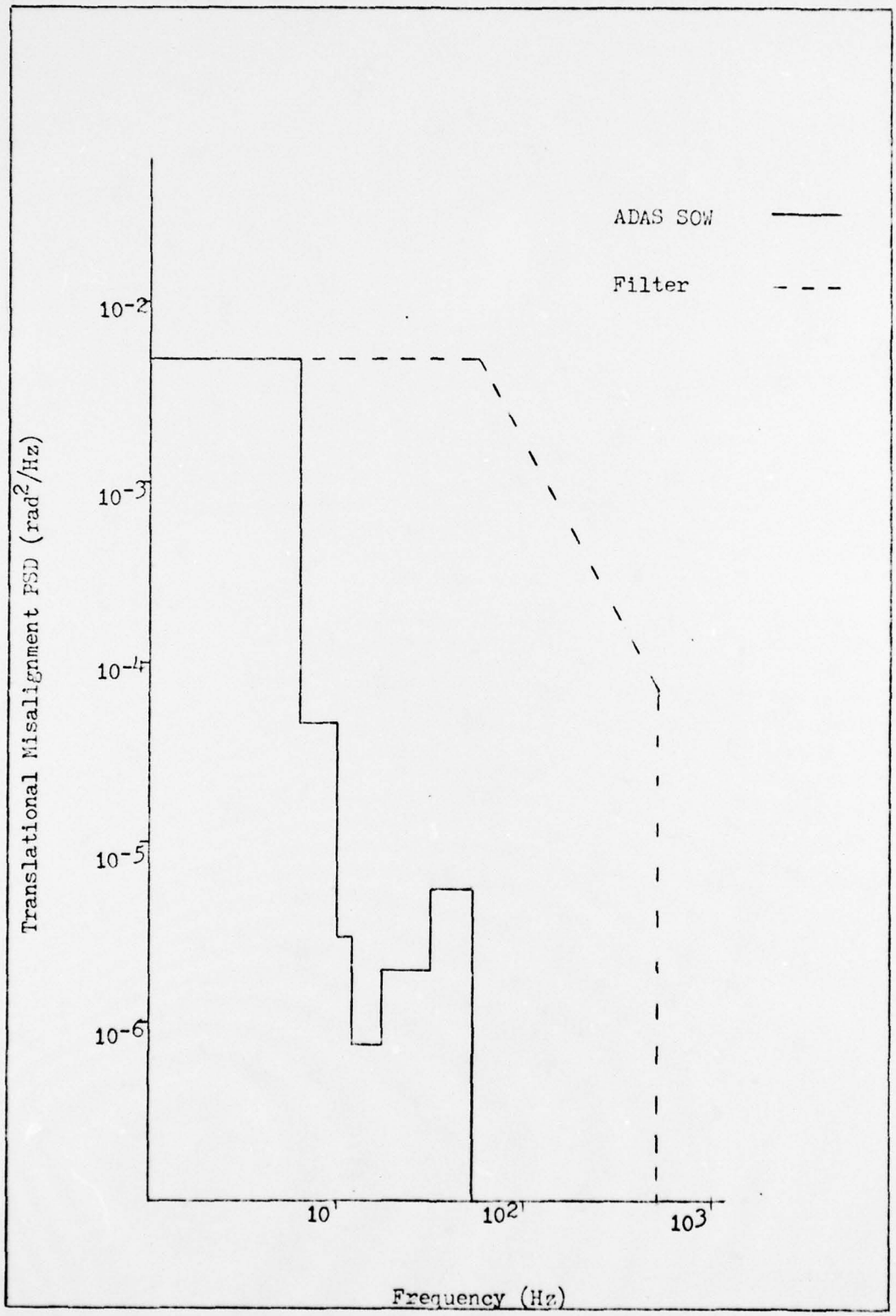


Fig.27. Comparison of Translational ADAS SOW and Filter PSDs

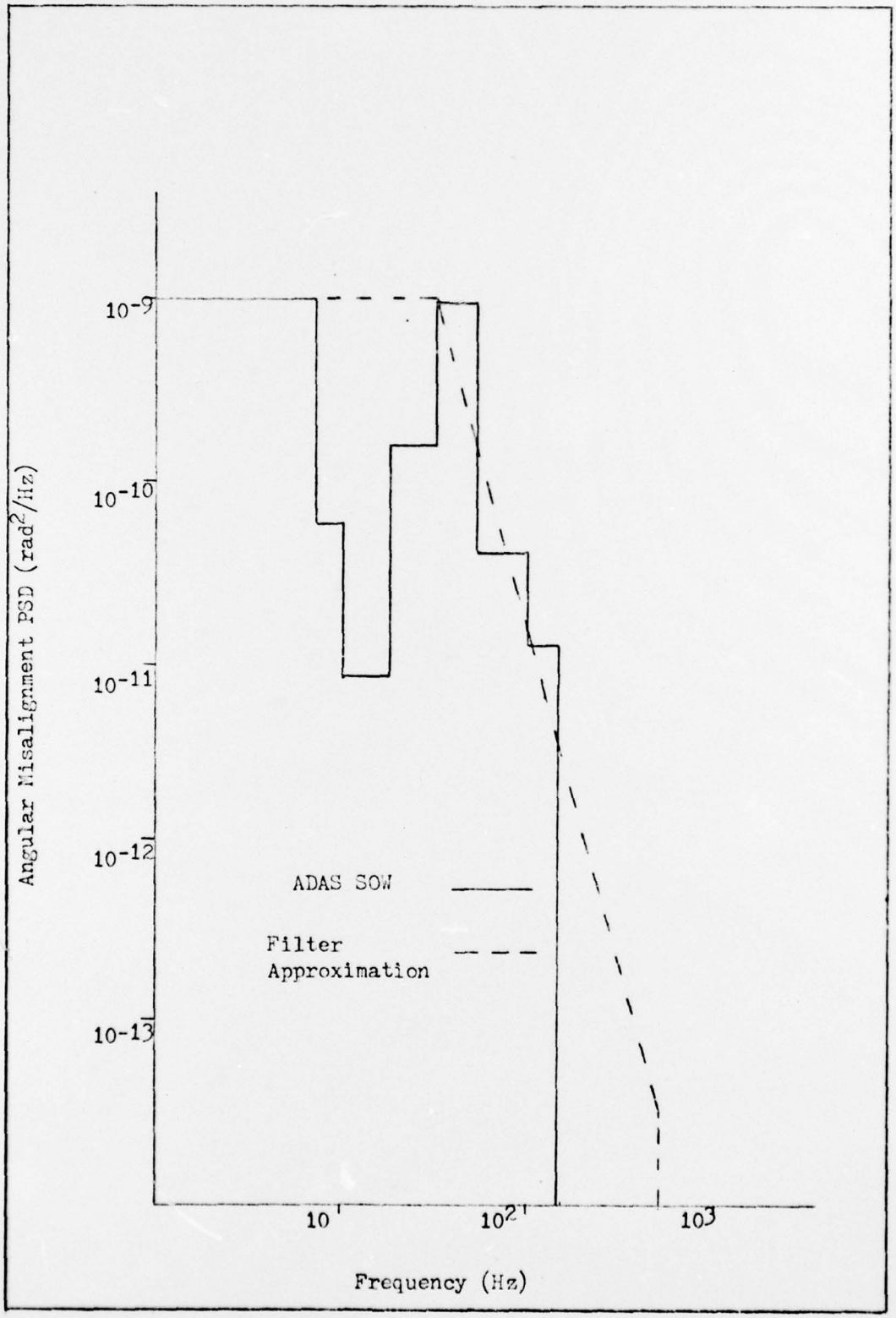


Fig.28. ADAS SOW PSD and State Space Filter Approximation

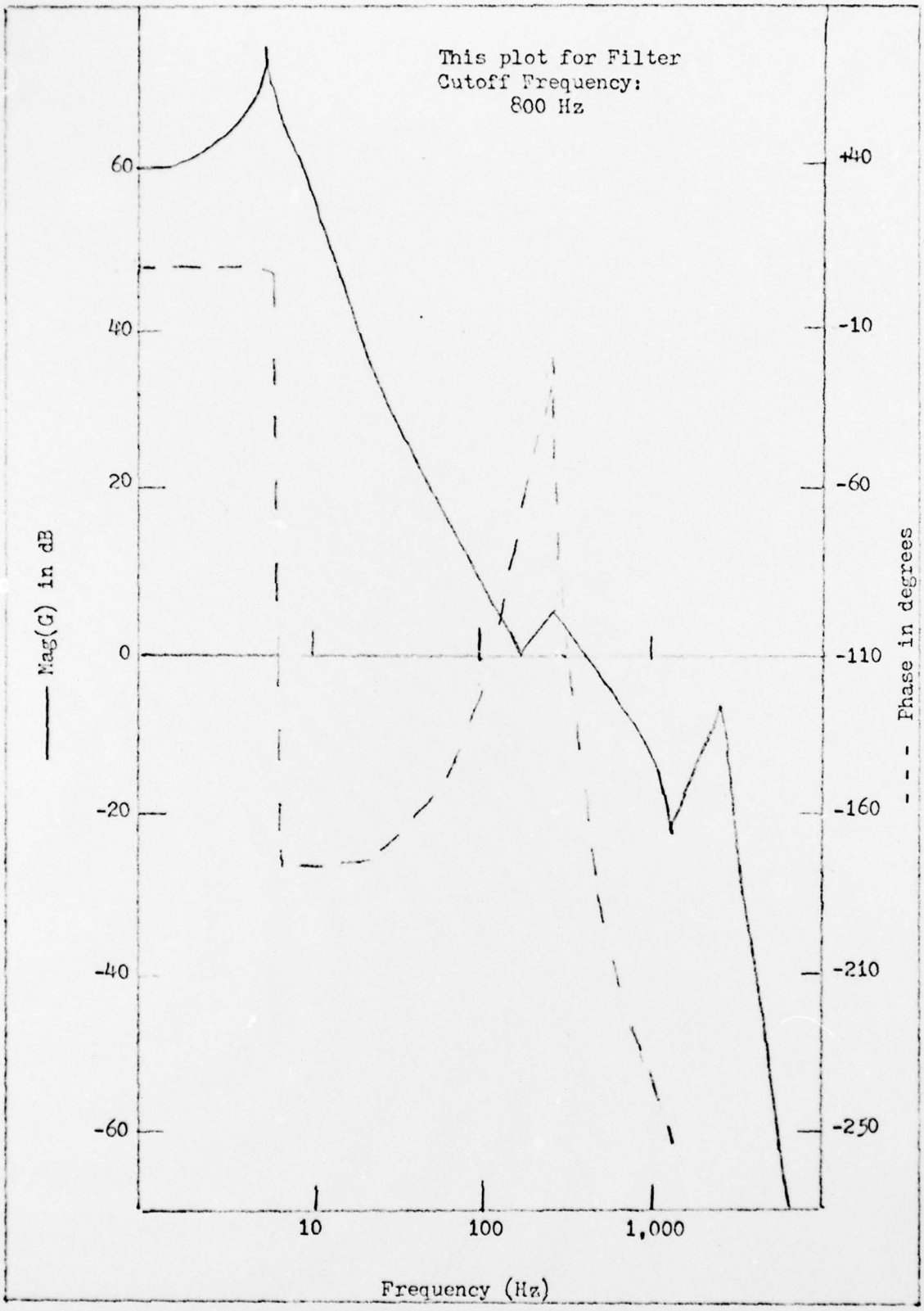


Fig. 29. ALPHA-P Open Loop Response

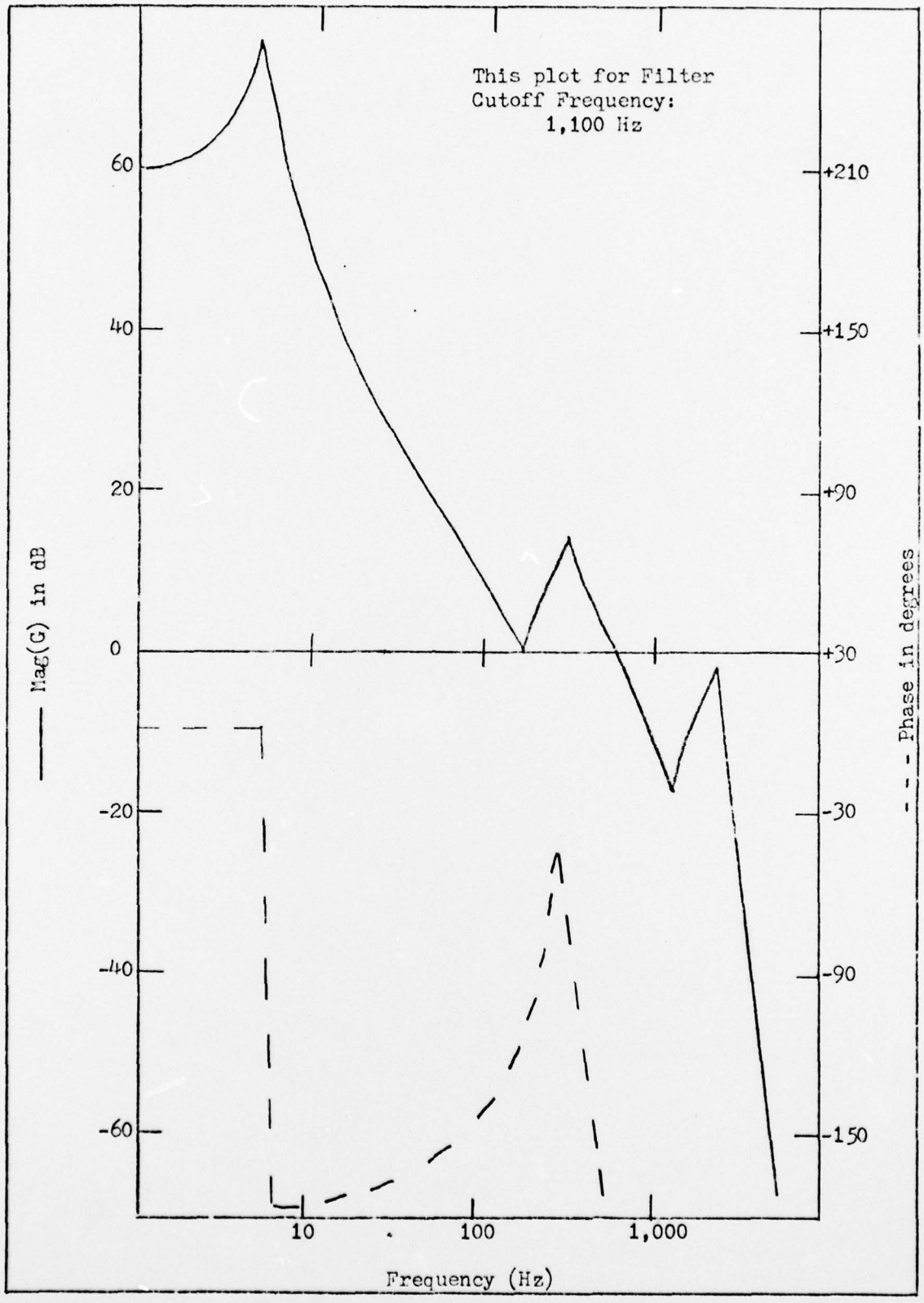


Fig. 30 . ALPHA-P Open Loop Response

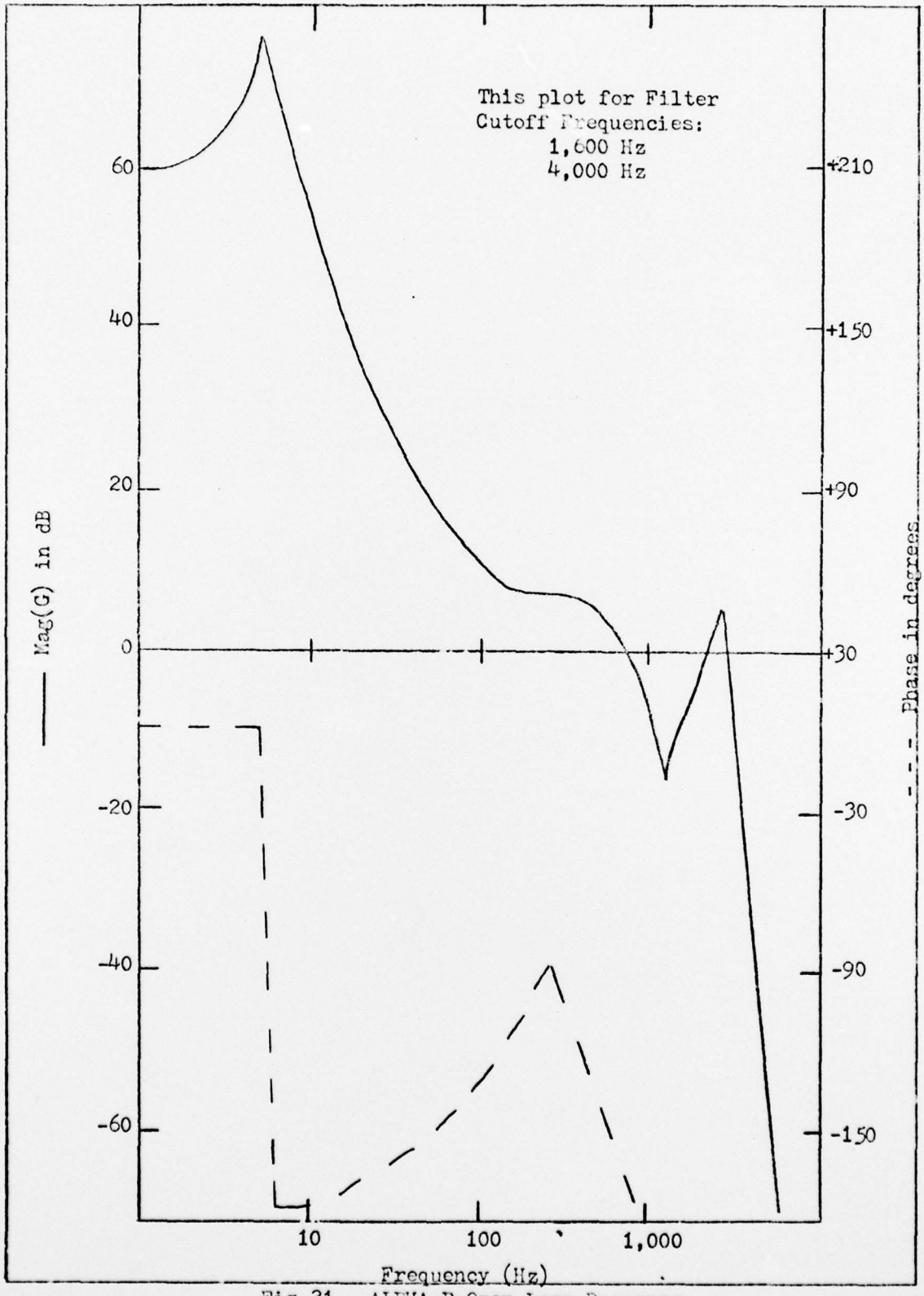


Fig.31 . ALPHA-P Open Loop Response

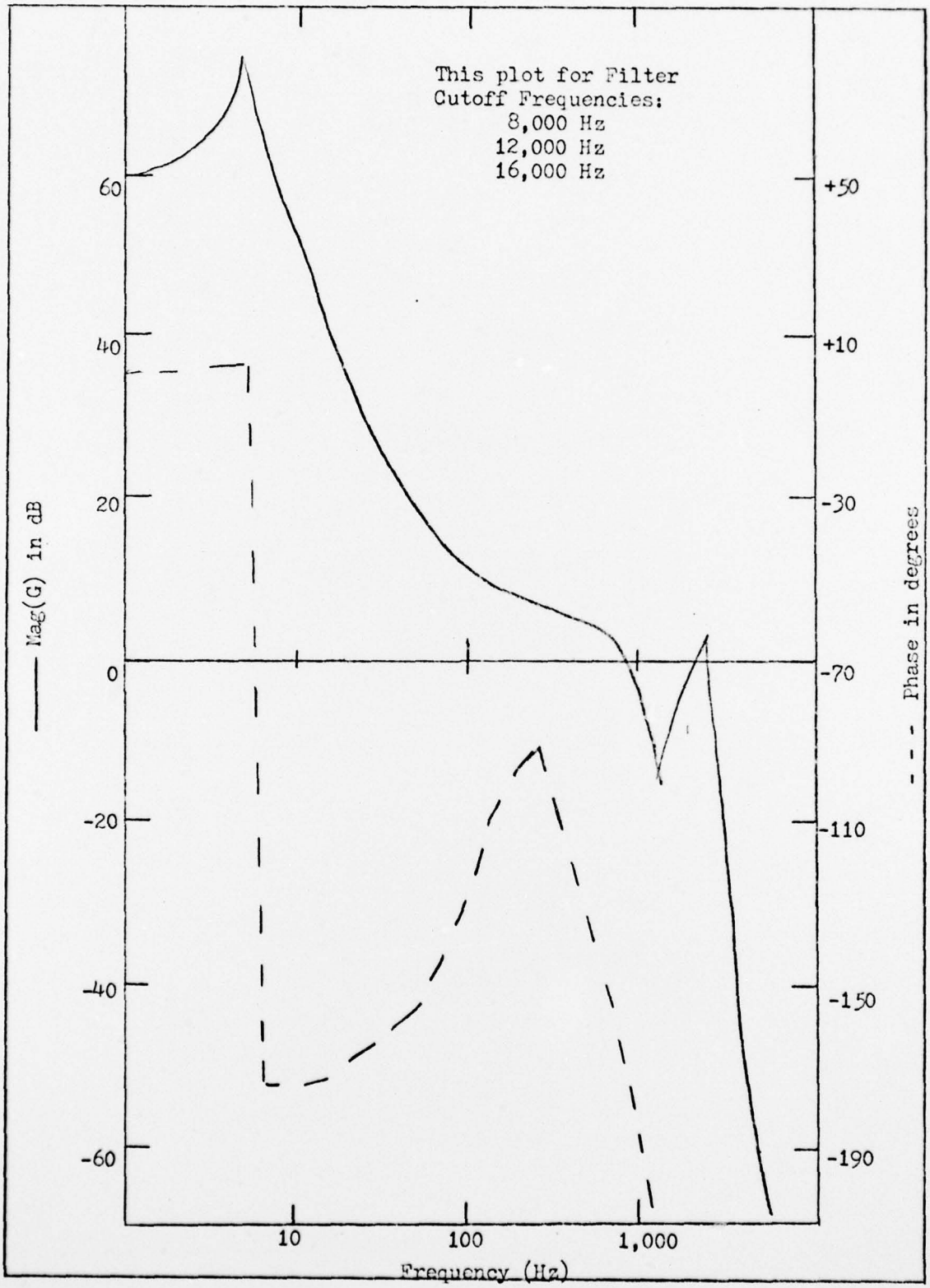


Fig. 32 . ALPHA-P Open Loop Response

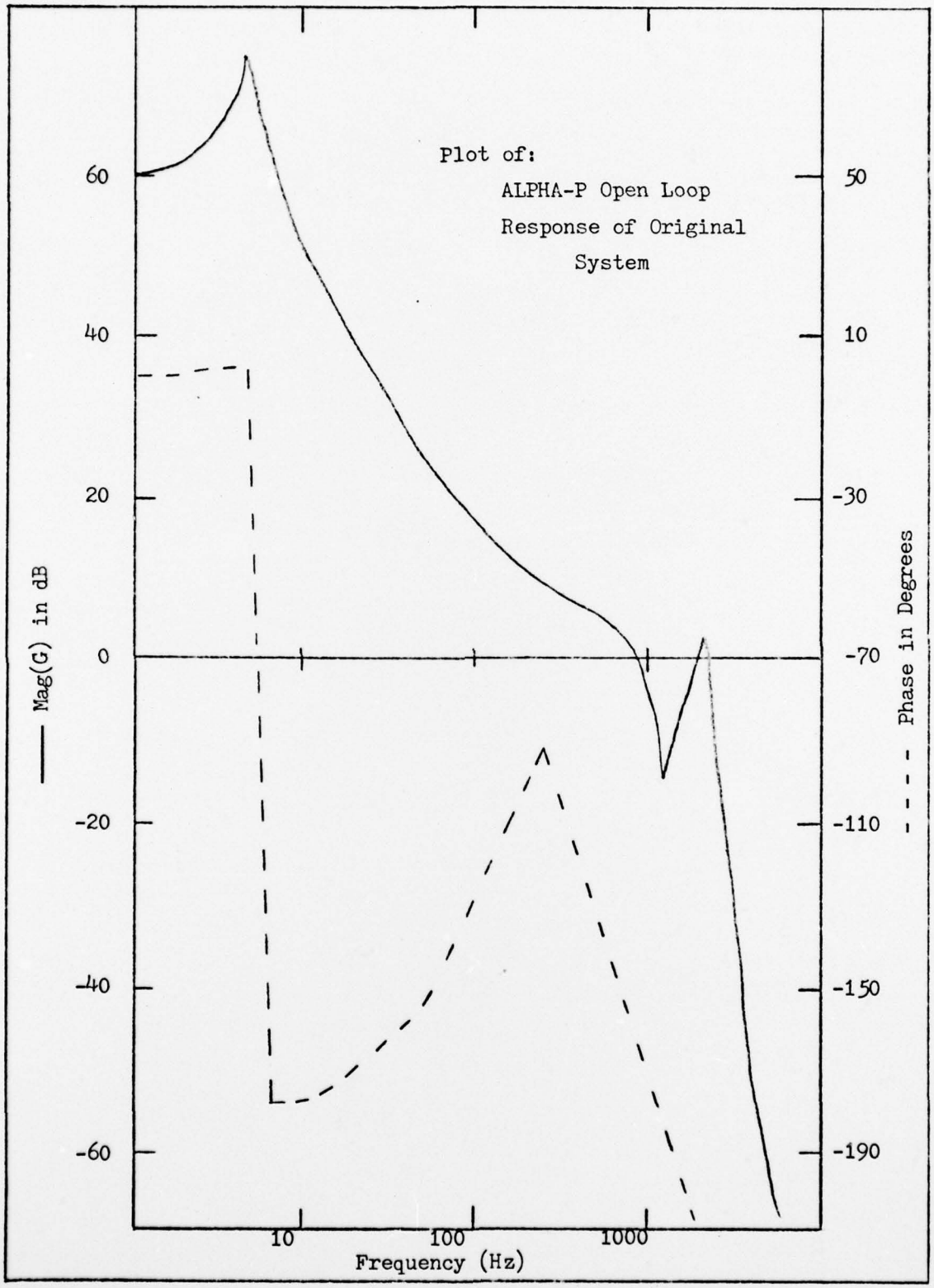


Fig.33. ALPHA-P Open Loop Response of Original System

Table XI

Eigenvalue Comparison with Various Filter Cutoff Frequencies

Cutoff Frequency (Hz)	Eigenvalues				
0	-11,517	+2,780	-1433 ±1137i	-418 ±148i	
32	-11,684	+3,089 ±2,168i	-2235 ±2966i	-1576	-1087
160	-11,843	+1,157 ± 994i	-1432 ±1131i	-805	-240
700	-13,166	+90 ±2,615i	-1388 ±1138i	-675	-402
800	-13,445	-170 ±2,797i	-1431 ±1106i	-590	-203
1,100	-14,410	-511 ±3,164i	-1483 ±1071i	-944	-94
1,600	-16,094	-1,250 ±3,338i	-1437 ±1092i	-768	-208
8,000	-51,231	-3,790 ±2,540i	-1350 ±1050i	-467 ±266i	
16,000	-100,570	-3990 ±1860i	-1390 ±1060i	-340	-760
160,000	-1,000,000	-4,200 ±1,090i	-1480 ±1080i	-827	-204
Infinite (Original System)		-4,184 ±844i	-1497 ±1086i	-897	-179

Vita

Patrick D. Nutz was born in Midland, Pennsylvania in February, 1954. He attended the University of Pittsburgh School of Engineering under a AFROTC scholarship. After graduating with a B.S. in Mechanical Engineering in April, 1976, he was commissioned a 2d Lt in the U.S. Air Force Reserve. His first assignment was to the Air Force Institute of Technology WPAFB in September, 1976.

Permanent address: 1111 Avondale Dr.
Industry, Pa. 15052

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Airborne Mirror Alignment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study deals with an electronic control system modification to solve a torque limitation problem in the Airborne Dynamic Alignment System aboard the Airborne Laser Lab. This control system is reduced in complexity and modeled in the frequency and state space domains. Closed loop system response over a desired frequency range is obtained from the frequency domain model. Stability data is calculated through eigenvalue analysis of the state space model. A low pass filter is introduced to decrease the demand on the torque saturated motor. The main result of this modification is that the filter does not appreciably

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alter the closed loop response. This is due to the fact that the cutoff frequency of the filter must be extremely high to keep the modified system stable. It is concluded that the complimentary filter does not solve the torque saturation problem. A recommendation is made that further analysis be concentrated in the time domain through modern state space techniques and the design approach to an optimal controller is presented.